C. Z. Rosecrans

An Experimental Study Of The Explosions Of Gaseous Mixture

AN EXPERIMENTAL STUDY OF THE EXPLOSIONS OF GASEOUS MIXTURES

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY CRANDALL ZACHARIAH ROSECRANS, B.S., 1919.

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AN EXPERIMENTAL STUDY
OF THE
EXPLOSIONS OF GASEOUS MIXTURES

I. Introduction.

Purpose and Scope of Investigation.

The purpose of this investigation is the study of some of the physical phenomena involved in the explosions of gaseous mixtures in a closed vessel. The problems connected with the chemical changes involved, or any of the other incidental problems arising, have not been considered within the scope of this investigation.

It is the purpose of this discussion to point out various comparisons existing between explosions taking place in different shaped vessels. These vessels were designed to simulate the various forms of combustion spaces actually in use in modern gas engines.

Acknowledgments.

The writer is indebted to A.P.Kratz, Research Assistant Professor in the Department of Mechanical Engineering, for much of the apparatus employed in this investigation

as well as for his supervision of the present investigation. The apparatus was designed and built by Professor Kratz during the years 1915-1916, and some of the preliminary results were obtained by him. These results are embodied in this discussion, as hereinafter noted. The apparatus was then remodeled, and additional results obtained by the writer.

General Consideration of Explosions in a Closed Vessel.

Consider a homogeneous mixture of any inflammable gas and air enclosed in a vessel with heavy metallic walls. The gas is assumed to be at atmospheric temperature, as is also the vessel. If an igniting agent, such as an electric spark, be communicated to the gas mixture, inflammation will take place, more or less rapidly, according to the nature of the mixture. The heat developed by the combustion will raise the temperature of the gases, and hence the pressure in the vessel. At the same time the gas is losing heat to the cold wall of the vessel. This loss of heat reduces the heat available for raising the pressure of the gas. At an instant when the loss of heat to the walls exactly balances the heat developed from the combustion, the pressure ceases to rise. This point on the pressure curve may be known as the "maximum pressure". The gas then cools slowly, by losing heat to the walls of the vessel, which, owing to its large mass in comparison with the mass of the gas, does not become appreciably heated. The pressure of the gas decreases as this cooling process goes on, and finally attains the original pressure

of the gas mixture, as charged into the vessel, but with any slight difference which might be caused by the contraction or expansion of the gases due to the chemical combination.

The time elapsing from the instant of ignition (that is, of the passing of the spark) to the instant of attaining maximum pressure will be designated as the "time of explosion". The ratio of air to gas, by volume, as originally charged into the vessel, will be known as the "air-gas ratio", or "R".

It is the purpose of this discussion to compare the maximum pressures developed and the times of explosion for different mixtures, exploded in different shaped vessels.

An estimate will also be made of the amount of heat lost to the walls of the vessel during the time of explosion.

II. REVIEW OF PREVIOUS RESEARCHES

There has been a considerable amount of experimenting done on the physical phenomena involved in the explosions of gaseous mixtures. The work of some of the experimenters in this field will be discussed in the following paragraphs.

Dugald Clerk[1]

In 1884 Clerk exploded mixtures of Cambridge coal gas and air at various initial pressures and temperatures.

His explosion vessel was cylindrical in form and had a volume of 517 cubic inches. The pressure developed in the cylinder was measured by means of a Richards indicator, and the pressure diagrams were traced on a revolving drum. Jump spark ignition was used, with the spark occurring at the bottom of the cylinder. Explosions of hydrogen and air were also made in the same apparatus.

In a later series of experiments a cylinder 7" long and 7" in diameter was used. The Richards indicator was retained, but a slide, moving longitudinally, was substituted for the drum. The recording paper was fastened to the slide,

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[1] Dugald Clerk--The Gas, Petrol, and Oil Engine, p. 126.

and the slide was calibrated by means of an electrically driven tuning fork (having a frequency of 200 vibrations per second) which traced a curve on the recording paper.

Clerk's curves, showing the relation between maximum pressure and air-gas ratio, and time and air-gas ratio are typical of all experiments in the field, and are reproduced in Fig. 1. A set of actual explosion curves for different air-gas ratios (taken with the later apparatus) is shown in Fig. 2.

Clerk's results are the best of those obtained from the early experimenters on gas explosions, but they are in error on account of the inability of the indicator to follow the rapid changes of pressure.

Massachusetts Institute of Technology[1]

Experiments similar to Clerk's were conducted at the Massachusetts Institute of Technology in 1898. The apparatus employed was similar to that used by Clerk, except that a rotating disc was used as the recording device. The pressures were therefore plotted on polar, instead of rectangular, coordinates.

The results closely approximate those obtained by Clerk and confirm all of his conclusions.

Experiments were also made with this apparatus on mixtures of gasoline vapor and air.

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[1] Clerk--The Gas, Petrol, and Oil Engine, p. 148.

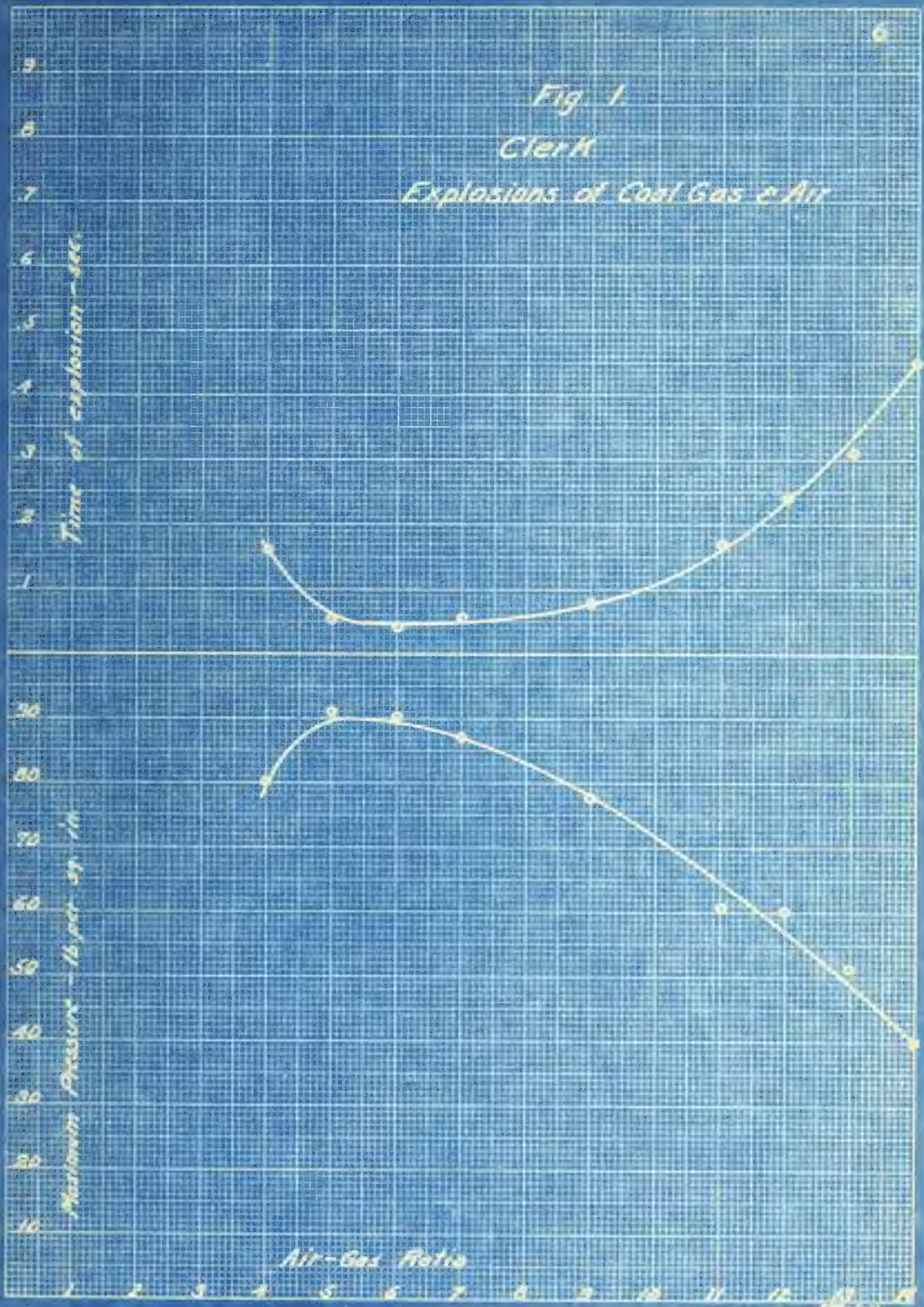
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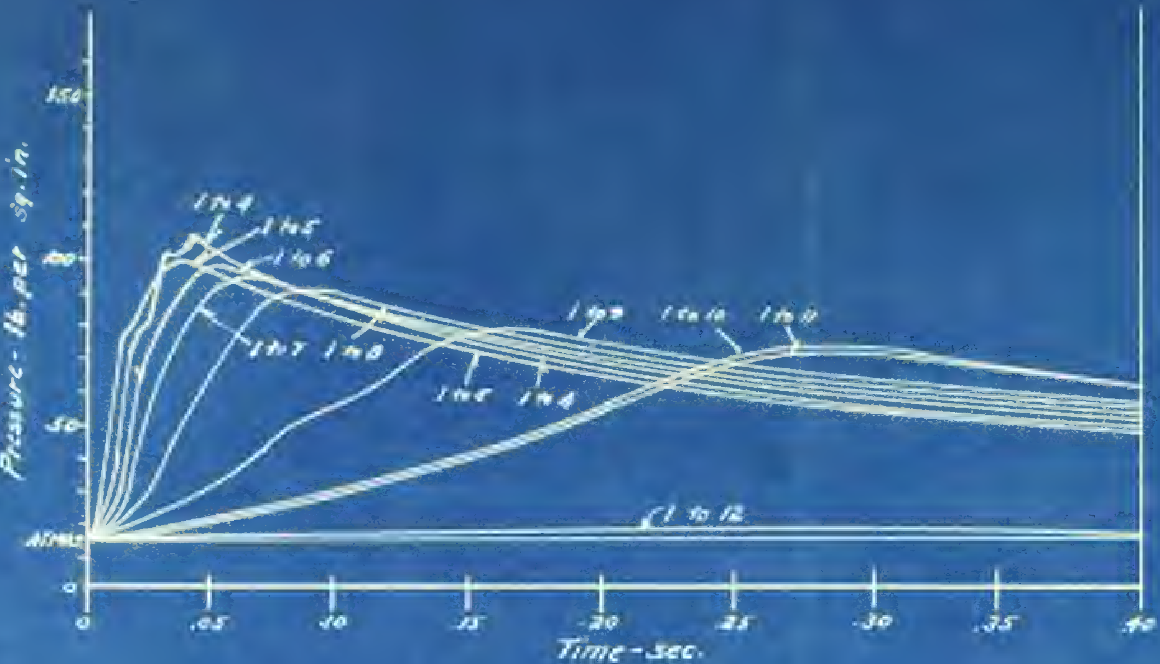
Fig. 1.
Clerk
Explosions of Coal Gas & Air
Time of explosion – sec.
Maximum Pressure – lb. per sq. in.
Air-Gas Ratio



Explosion Curves of Coal Gas and Air Mixtures.

-CLERK.-

Fig. 2.

Grover[1]

In 1895 F. Grover made some experiments on the explosions of mixtures of coal gas and air in an apparatus much the same as Clerk's. The explosion vessel had a volume of one cubic foot. It was 8" in diameter and 34" long. A Crosby indicator was used to determine the pressure developed, and a tuning fork to record the time. The mixture was introduced by filling the cylinder with water, and allowing the gas and air to enter as the water flowed out.

The results of Grover's work, when explosion (or maximum) pressure was plotted against the air-gas ratio, gave curves falling much below those obtained by Clerk and at the Massachusetts Institute of Technology, although the calorific value of the gases was practically the same in all cases. Grover accounts for this difference by the fact that the heat taken to evaporate the water adhering to the cylinder walls after drawing in the gas charge reduced the heat available for raising the pressure. It is probable, however, that his method of introducing the mixture was not as conducive to thorough mixing as the method used in Clerk's researches. It is a well known fact that a lean mixture will ignite much more rapidly if a small amount of relatively strong mixture is situated in the immediate vicinity of the ignition point. The time of explosion was shorter in Grover's work than in the

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[1] Clerk--The Gas, Petrol, and Oil Engine, p. 153.

previously described experiments, in almost every case, and this fact seems to indicate that the lower pressures developed in Grover's experiments were due to faulty mixing of the charge.

Grover also made explosions with mixtures consisting of coal gas, air, and exhaust gas left from the preceding explosion. His results indicated that the presence of from 5% to 30% of exhaust gas in the initial gaseous mixture actually raised the pressure as much as 19 lb. per sq. in. above that observed for a mixture containing the same percentage of fresh coal gas. This apparent increase of maximum pressure became less as the strength of the mixture increased, and with a 12 to 1 mixture the effect became negligible. With a 7 to 1 mixture the maximum pressure was decreased by the presence of exhaust gas. This fact, together with an analysis of the exhaust gas, proved conclusively that the increase of pressure with the weaker mixtures was due to the fact that the exhaust gases contained as high as 30% of inflammable gases remaining from the previous incomplete combustion. The obvious conclusion is that the products of combustion, unless they contain unburned gases, cannot raise the explosion pressure when used as a diluent.

Grover later (1898) made explosions of acetylene and air mixtures, using the same experimental apparatus. The gas, however, was measured in from a gas holder, and the error due to the water left in the cylinder was thereby

eliminated. Low tension make and break ignition was used, the spark occurring at the center of the cylinder.

The mixtures were exploded at 1, 2, and 3 atmospheres initial pressure. (Mixtures of coal gas and air were also exploded at the same initial pressures). The results, however, still show evidence that a perfectly homogeneous mixture was not obtained, as the coal gas explosion pressures are again low as compared with Clerk's.

Curves of explosion pressure plotted against initial pressure are given in Fig. 3. From these curves it is evident that the explosion pressure increases almost directly as the initial pressure. The deviation from a straight line law may be explained by the poor mixing of the charge evident in all Grover's work, since the straight line law was confirmed by later experimenters.

Curves of pressure and time of explosion for different mixtures of acetylene and air, and coal gas and air are given in Fig. 4.

Petavel[1]

Petavel's experiments (1902) on the explosion of gaseous mixtures are of great interest, as they are the only ones carried out at very high initial pressures. A spherical steel bomb having an internal diameter of 4" and a volume of 0.0195 cu. ft. was used.

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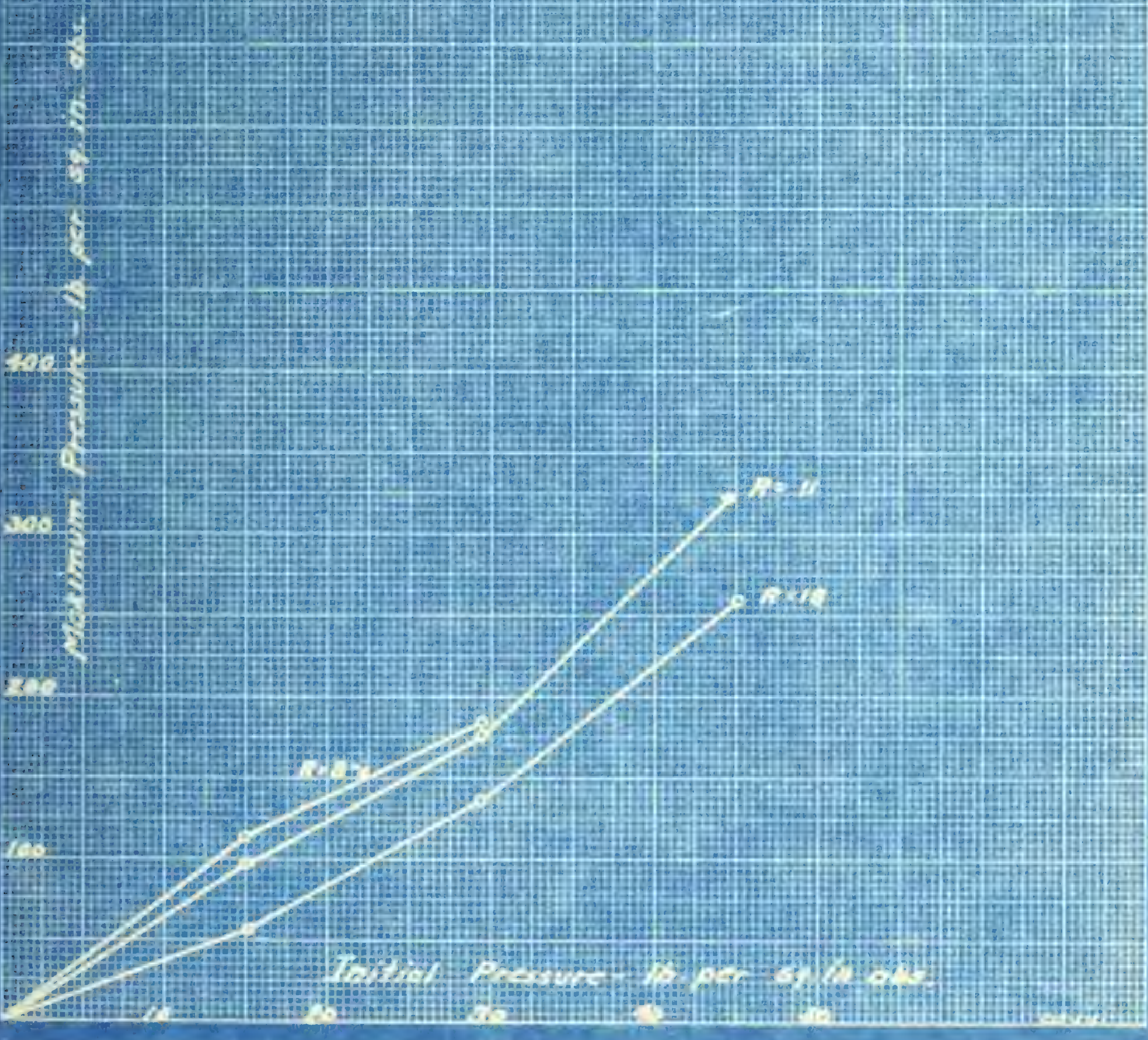
[1] Memoirs of Manchester Lit. and Phil. Soc. v. 46, part 2, p. 1.

Fig. 3.

GROVER

Effect of Initial Pressure

Acetylene & Air



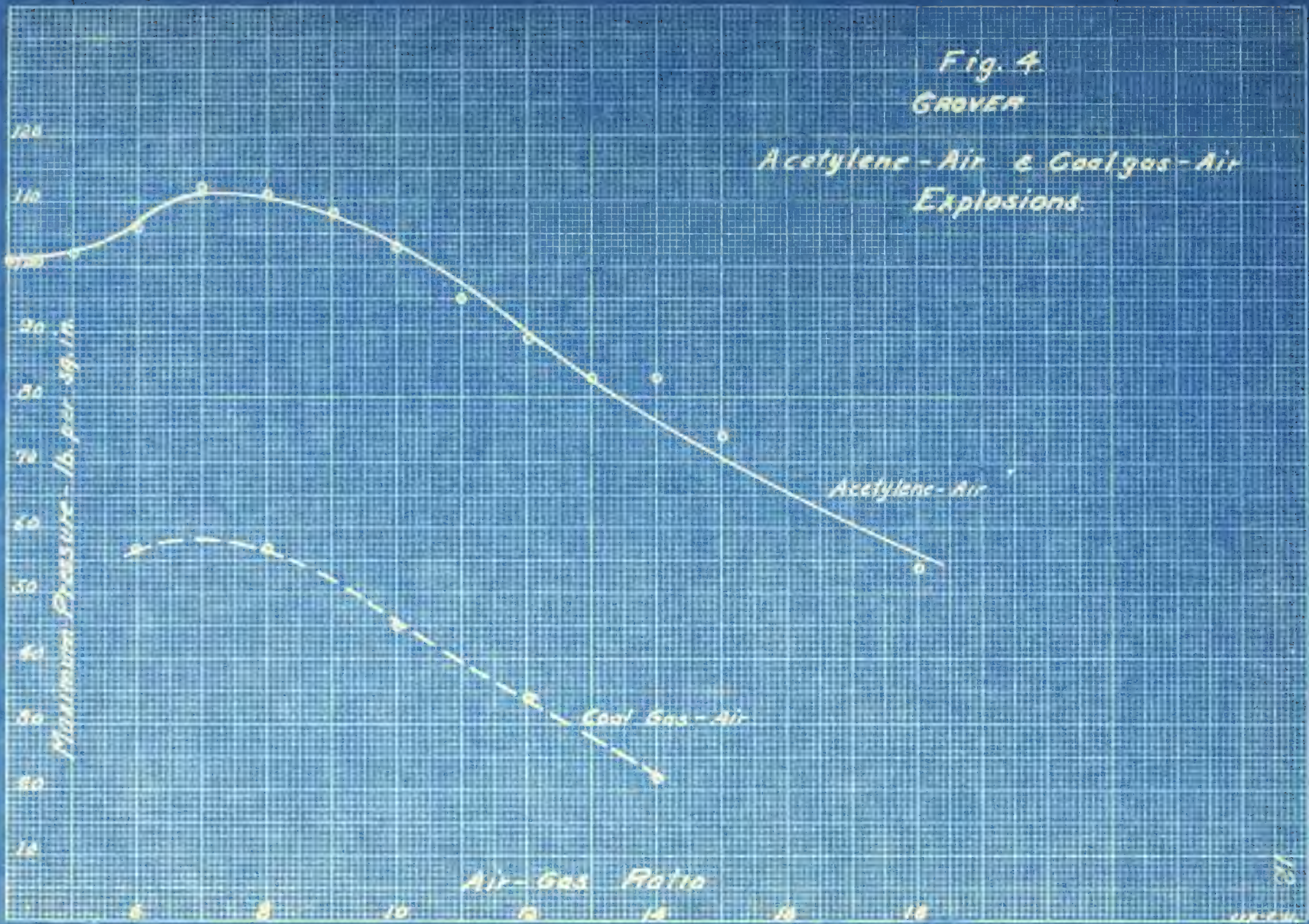


Fig. 4
GROVER
Acetylene-Air & Coalgas-Air
Explosions.

Petavel's indicator was a great improvement on those used before. A steel tube, ending in a piston, and loaded as a hollow column was used as the spring, and the motion was greatly magnified by a system of levers and a mirror. The instrument was practically free from all inertia effects, and seemed to be able to follow the rapid pressure variations without appreciable lag.

Bairstow and Alexander[1]

Explosion experiments were made in 1905 by Messrs. Bairstow and Alexander, using mixtures of coal gas and air. Their apparatus was exceedingly complete, and provisions were made for the most accurate measurements possible. The indicator, a Simplex, of the ordinary steam engine type, was, as usual, the weakest part of the apparatus. The explosion vessel was 18" long and 10" in diameter, and had a volume of 0.821 cu. ft. The gas used the the city illuminating gas, and it averaged 628 Btu. per cu. ft. in heating value.

Bairstow and Alexander found the same difficulty in getting a perfectly homogeneous mixture that Grover did. Mixtures were allowed to stand as long as 17 hours without diffusing enough to be ignited. A mixing plate, operated by hand, was therefore added. Ignition was accomplished by means of a jump spark, through a "firing tube". This tube extended some distance down into the interior of the vessel,

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[1] Proc. Roy. Soc., Series A, v. 76, p. 345.

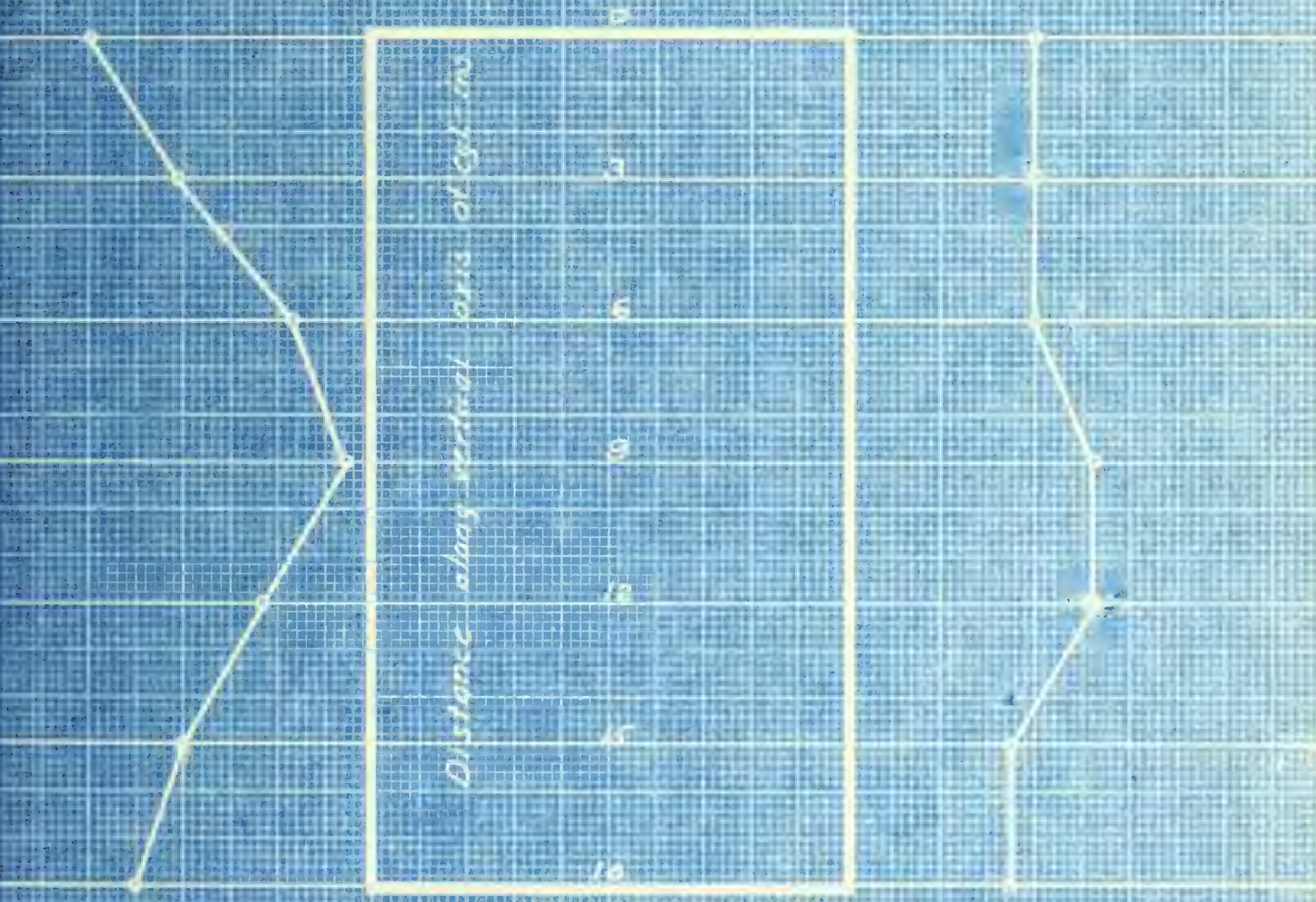
and was pierced with small holes at intervals. The electrical ignition device was situated at the top of the tube. All holes in the tube were plugged except one located at the desired distance from the top of the cylinder, and the electric ignition spark was passed. The mixture in the tube exploded, throwing a jet of flame into the main part of the explosion vessel through the hole in the firing tube, and igniting the whole mixture. The position of the open hole in the tube was changed to give ignition at any desired point of the vessel.

Ignition accomplished by this means was not constant in igniting power, as the greater amount of gas exploded in the firing tube when the lower hole was open projected a jet of flame farther into the main vessel than it did when the upper holes were open. This caused some variation in the maximum pressures and times of explosion of the mixtures in the vessel, due to the change in igniting power of the firing tube. With electric ignition, the spark gap being placed at the desired point in the vessel, this effect is eliminated.

Fig. 5 shows the time of explosion and the maximum pressure as affected by the position of the ignition point, a 7 to 1 mixture being used in all the experiments. The initial pressure was 35 lb. per sq. in. absolute. Similar experiments were made with a weaker mixture, in which case it was found that the position of the ignition point for most rapid combustion was about three inches below the center of

BAIRSTOW & ALEXANDER

Effect of Ignition
Fig. 5



the vessel. This can be accounted for by the fact that the convection currents in the weaker mixture are sufficiently rapid to be comparable with the rate of inflammation. The position of the ignition point in the lower part of the vessel assists the convection currents.

In all the following experiments made by Bairstow and Alexander, four sparks in series, passing through the axis of the cylinder were used. Two complete series of tests were made, with varying mixtures, one series at 55 lb. per sq. in. absolute initial pressure, and the other at 34.5 lb. per sq. in. absolute. The results are plotted in Fig. 6.

It is questionable whether the results of the experiments on ignition at different points of the vessel are very accurate or significant, since the variation in the igniting power of the firing tube, as pointed out above, might cause a wide variation in the maximum pressure and the time of explosion.

The results of the pressure experiments as shown in Fig. 7 indicate clearly that the maximum pressure is directly proportional to the initial pressure (absolute). Further data on the cooling of various mixtures after explosion were given by these experimenters. These data will be discussed later.

Fenn[1]

In 1900 Robert H. Fenn, working at the Clarkson

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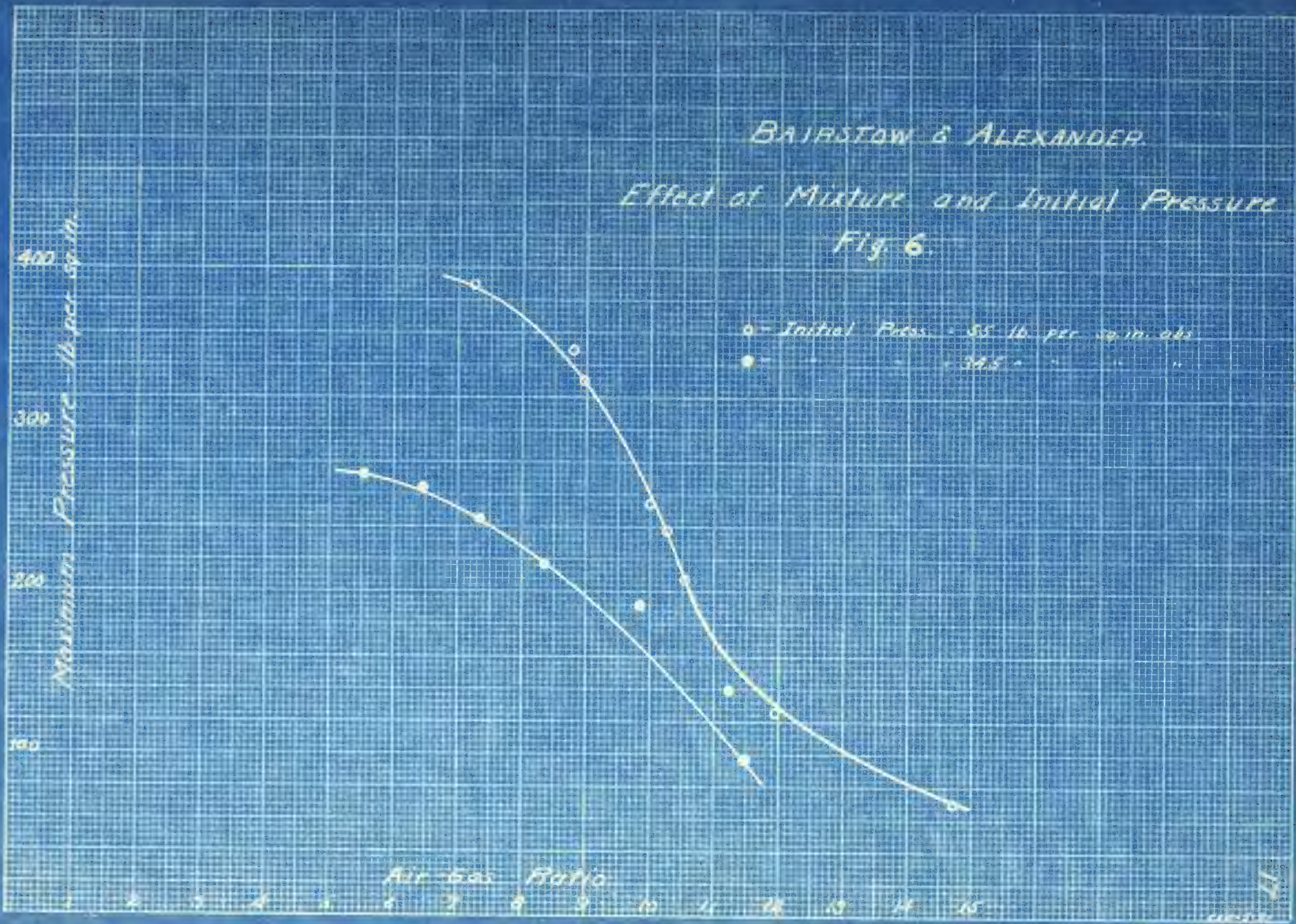
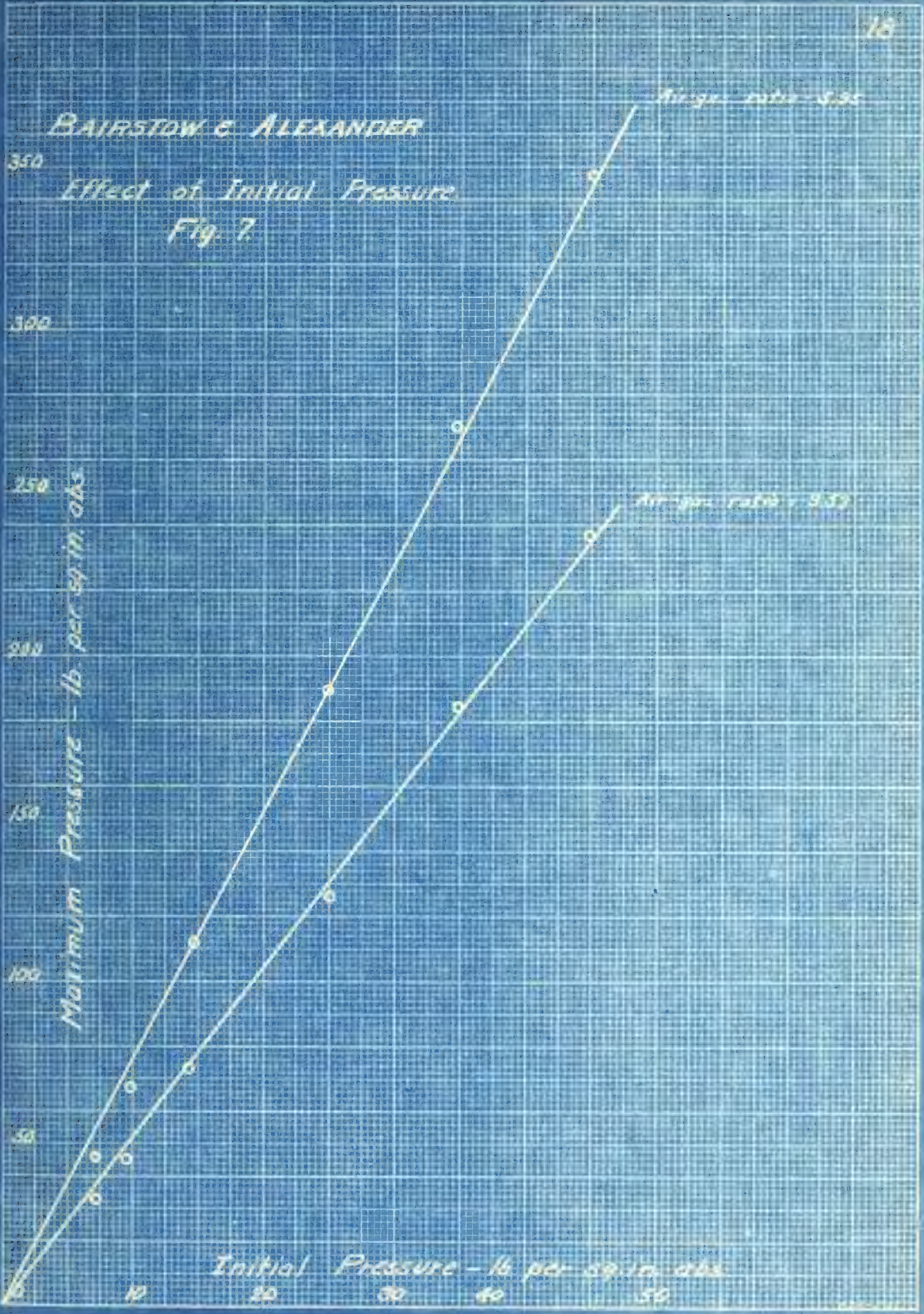
[1] Engineering News, v. 44, p. 366.


BAIRSTOW & ALEXANDER
Effect of Mixture and Initial Pressure
Fig. 6.
o - Initial Press. - 55 lb. per sq. in. abs
● - " " - 34.5 " " " "
Maximum Pressure lb. per sq. in.
400
300
200
100
Air Gas Ratio
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
17


BAIRSTOW & ALEXANDER
Effect of Initial Pressure
Fig. 7
Air-gas ratio = 5.95
Air-gas ratio
Maximum Pressure – lb per sq. in. abs
Initial Pressure – lb per sq. in. abs
350
300
250
200
150
100
50
0
10
20
30
40
50

School of Technology, exploded mixtures of acetylene and air, and gasoline vapor and air in a cylinder with a moveable piston. His results merely confirm those heretofore given, especially in regard to the relation of maximum pressure to initial pressure.

Bairstow and Horsely[1]

During the year 1902 Bairstow and Horsely ran a series of explosions at two different initial pressures. The results seem to indicate that the explosion pressures are not exactly proportional to the initial pressures for the same mixture, but that the ratio of explosion pressure to initial pressure increases slightly with the increase of initial pressure. These explosions were made in the same apparatus which was used by Bairstow and Alexander.

Hopkinson[2]

Perhaps the most important and conclusive researches in the field were made by the late Professor Hopkinson, of Cambridge. His researches were made with Cambridge coal gas, in a comparatively large cylinder (6.2 cu ft. in volume). Experiments were made with 9 to 1 and 12 to 1 mixtures, using gases saturated with water vapor in all cases.

Hopkinson's original optical indicator was used in all this work, and was the first instrument to be employed

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[1] Engineering, v. 74, p. 723.

[2] Clerk,-The Gas, Petrol, and Oil Engine, p. 185.

which was without doubt capable of following the rapid variations of pressure during the explosions. For a detailed description of this indicator, reference may be made to the Proceedings of the Institute of Civil Engineers, vol. 143.

Hopkinson also measured the temperature of the burning gases by means of platinum resistance thermometers inserted at different parts of the vessel, as shown in Fig. 8. The time lag of the thermometers was determined by separate experiments and corrections were applied to the results. The thermometers consisted of short coils of platinum wire 0.001" in diameter, connected in a galvanometer circuit in such a way that the change in resistance due to the change in temperature caused a variation in the current in the galvanometer, and therefore caused the galvanometer mirror to deflect. Records of temperature and pressure were taken on a photographic film, fastened on a revolving drum. The thermometers were placed as follows:- one at 30 cm. from the ignition point; and one very near the wall of the vessel. The center coil was almost invariably melted when the charge was fired, indicating that the temperature near the ignition point was at least as high as the melting point of platinum (1755 deg. C). Fig. 9 shows the curves of temperature at the center of the vessel, and pressure, plotted against time. It may be noted that the platinum wire melted about 0.025 sec. before the attainment of maximum pressure. The temperature at the start of inflammation rose rapidly. This indicated that the

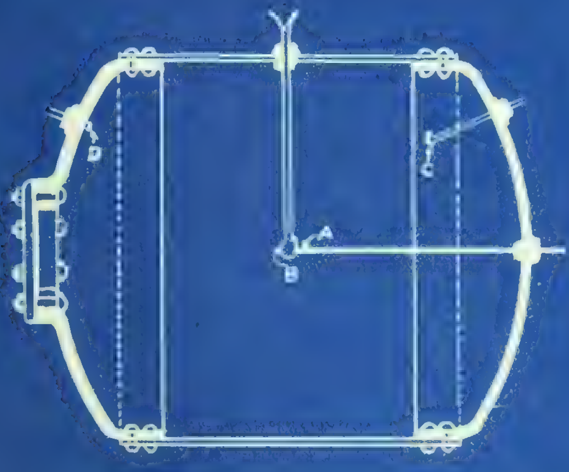

Fig. 8.
Hopkinson's Explosion Vessel

Ignition Point	A
Resistance Thermometer at center	B
" " 10 cm. from wall	C
" " 1 " " "	D

Volume of vessel = 0.684 cu. ft.

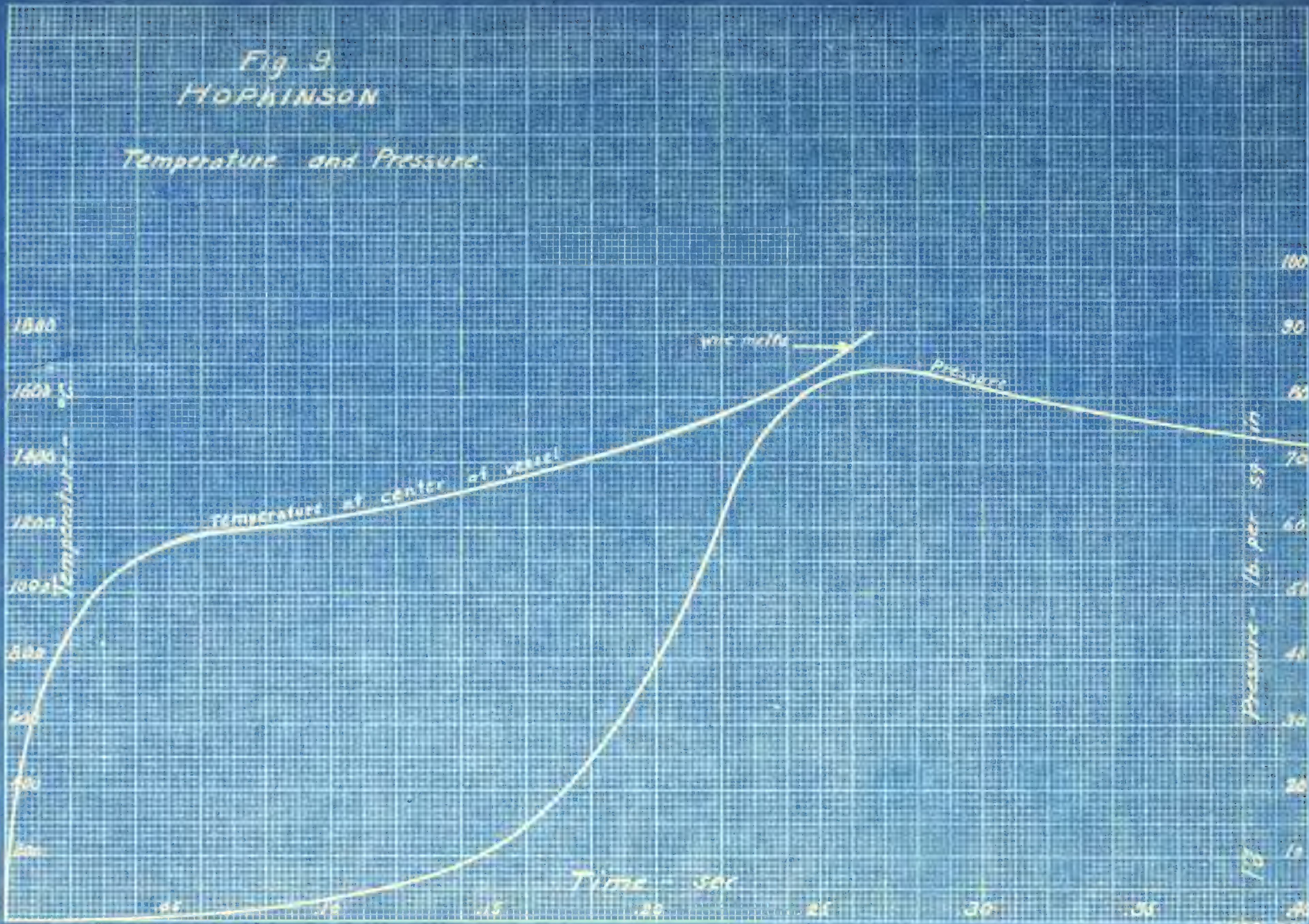

Fig. 9.
HOPKINSON
Temperature and Pressure.
Temperature at center of vessel
Pressure
Time - sec
Pressure - lb per sq in
Temperature

combustion of the mass of gas near the ignition point was practically complete before the pressure had increased more than two or three pounds (as shown by the indicator).

The flame then spread through the mixture with a velocity of approximately 150 cm. per second, and completely filled the vessel about 0.03 sec. before the attainment of the maximum pressure. This was shown by the fact that the temperature as recorded by the thermometer placed 1 cm. from the walls attained a maximum about 0.03 sec. before the pressure. The gas at the center was then compressed adiabatically to a temperature considerably above the melting point of platinum, probably about 1900 deg. C.

At the moment of maximum pressure the temperature distribution was approximately as follows:-

Mean (calculated from pressure)..	1600 deg. C.
Center, near spark	1900 " "
10 cm. within wall	1700 " "
1 cm from wall at end	1200 " "
1 cm from wall at side	850 " "

It is evident that even if the experiments were performed in a nonconducting vessel, differences in temperature would exist at different parts of the vessel, due, not to the conduction and radiation phenomena, but to the different degrees of compression existing at the different points of the mixture.

At a time 0.05 sec. later than the attainment of maximum pressure, the mean temperature of the gas, calculated from the pressure, was about 1100 deg. C. The mean

temperature (exclusive of a layer 1 cm. thick at the walls) was determined by a long platinum wire stretched entirely across the vessel. This temperature was found to be 1160 deg. C., a value reasonably close to the calculated mean value.

In the explosion of a weaker mixture (12 to 1), convection became more important due to the fact that the flame was propagated more slowly. The temperature immediately below the spark at first rose, then decreased as the cold unburned gased moved upward following the ascending flame. One second after ignition the pressure was still less than 10 lb. per sq. in., and the upper half of the vessel was filled with burned gas which was losing heat to the walls. The last portions of gas to be ignited were those immediately below the spark.

In the 12 to 1 mixture the maximum pressure was about 50 lb. per sq. in. and was attained 2.5 sec. after ignition. During half of that time at least half of the superficial area of the vessel had been in contact with the flame. Thus the loss of heat before the attainment of maximum pressure was probably greater in a weak mixture than in one of greater strength.

In some subsequent experiments Hopkins undertook to measure the heat loss to the wall. For these experiments he used a cast iron cylinder 1 foot in diameter and 1 foot long, which was lined with wood. The wood was overlaid with a continuous grid of strip copper, $\frac{1}{4}$" wide and 0.04" thick, which was connected by wires to a galvanometer circuit, in order to

record the change in resistance of the strip as it was heated by the explosion. The record of the changes in resistance was photographed on a film, together with the pressure curve from the Hopkinson optical indicator. The results of calculations based on the data obtained are shown in Fig. 10. Hopkinson says, "The heat loss begins about 0.05 sec. after ignition, when the flame first comes in contact with the copper. At first the loss goes on at a very great rate, and by the time the maximum pressure is reached, about 1700 calories, or 12% of the gross heating value of the gas, has passed to the walls. The rate of heat loss at this point is about 10 calories per sq. cm. per sec., and the mean gas temperature is 1760 deg. C. At 0.2 sec. from ignition the rate of heat loss is about 3.5 calories per sq. cm. per sec., and the mean gas temperature is 1300 deg. C. The mean temperature is reduced in the ratio $\frac{74}{100}$ between these two points, but the rate of heat loss at 0.2 sec. is only one-third of what it was at maximum pressure."

Hopkinson's results from these experiments obviously include some of the radiation loss with the conduction losses, although Clerk states that only conduction losses are included.

Nagel[1]

In 1908 A. Nagel ran an elaborate series of experiments to determine the velocity of inflammation of various gases. His explosions were made in a spherical steel bomb

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[1] Mitteilungen uber Forschungsarbeiten, v. 54, 1908.

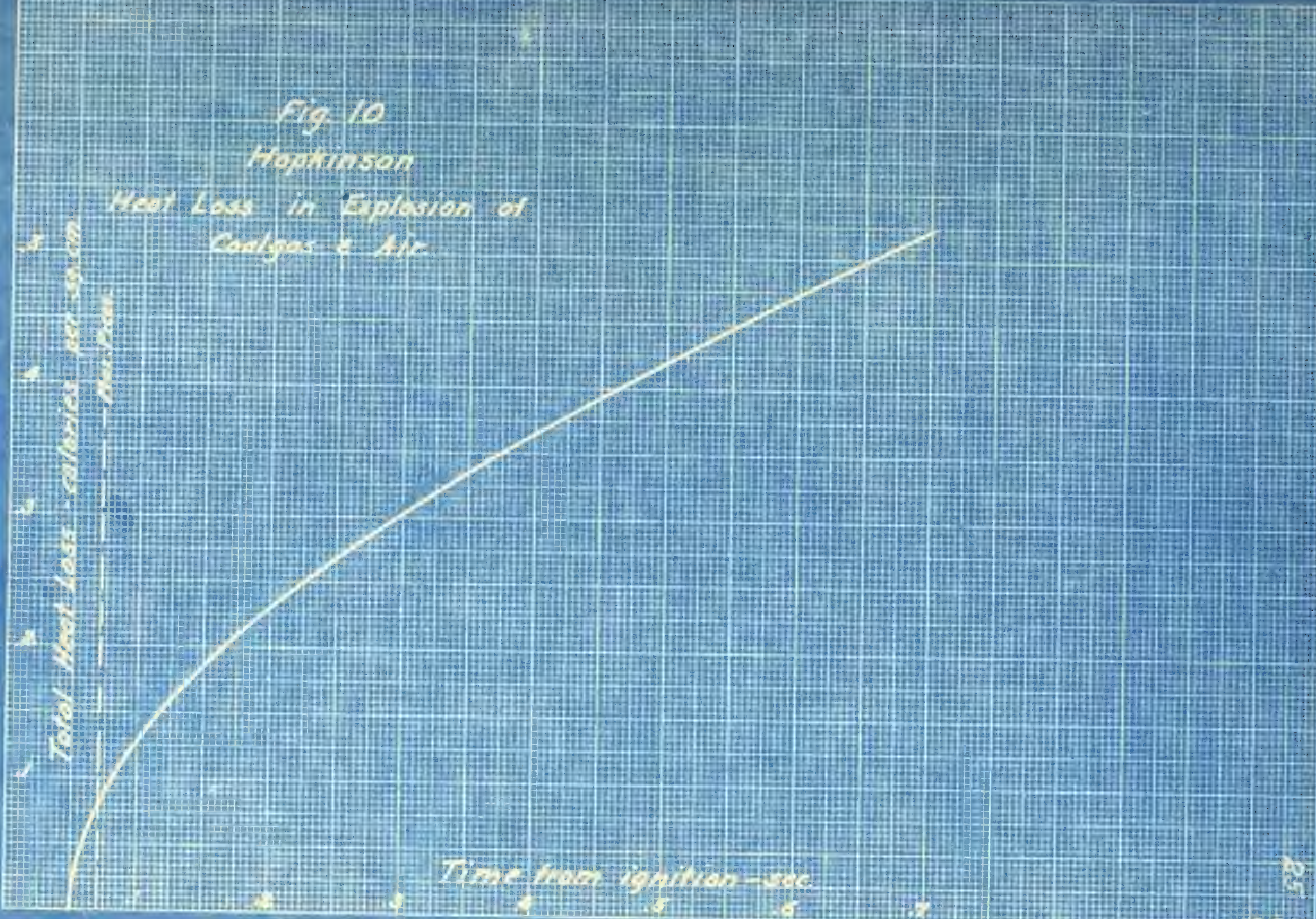


Fig. 10
Hopkinson
Heat Loss in Explosion of
Coalgas & Air.
Total Heat Loss - calories per sq. cm
Max. Press.
Time from ignition - sec.
.1
.2
.3
.4
.5
.6
.7

40 cm. in diameter. A diaphragm in communication with the bomb, and connected mechanically to a concave mirror, indicated the pressure developed by the explosion. Ignition was accomplished by means of a single jump spark occurring at the center of the bomb. All explosions were made with gases saturated with water vapor. No maximum pressures were given in the report of the results, as the experimenter was merely interested in obtaining the velocity of inflammation.

Nagel found that for hydrogen and air mixtures the inflammation velocity increased directly as the hydrogen content. With a constant mixture, the velocity increased with the pressure, the increase being greater as the mixture became richer. For illuminating gas and producer gas the velocity of inflammation also increased with the gas content. For these, however, at constant gas content, there seemed to be a tendency for the velocity to decrease with an increase of initial pressure. This effect was more marked with weak mixtures than with stronger. The effect of initial temperature is not sufficiently marked to justify any definite conclusions.

An elaborate mathematical analysis of the flame propagation in a spherical vessel is also given.

From the results of Hopkinson's experiments as quoted above it would seem that Nagel's conclusions are somewhat in error. Hopkinson clearly showed that inflammation might be complete, i. e., the flame might fill the entire

vessel, some time before maximum pressure was attained. Nagel took the time from ignition (passing of the spark) to the attainment of maximum pressure as the time of inflammation. His results and conclusions as to the velocity of flame propagation are therefore probably somewhat in error.

Bone and others.

In 1915 W. A. Bone, assisted by several other experimenters, made explosions of various hydrocarbons with oxygen and air. Two explosion vessels were used:-

1) a cylindrical vessel 1" in diameter and 8" long.
2) a spherical vessel 3" in diameter.

A Petavel indicator was used to indicate the pressures developed.

The experiments were conducted primarily to bring out facts relating to the chemical transformations involved in the explosion process, but the results also confirm the work done up to date in regard to the effect of varying the gas mixture and the initial pressure.

David.

Major W. T. David has conducted several series of researches on the explosions of gaseous mixtures, with special reference to the cooling phenomena during explosion and during the total cooling period. These will be discussed under their separate headings.

Radiation. These experiments were made with a cylindrical explosion vessel 30 cm. in diameter and 30 cm. long, and a Hopkinson indicator was used to record the

explosion pressures. A platinum bolometer, connected in a galvanomenter circuit, was placed in front of a diathermanous fluorite window at one end of the vessel. The change in resistance of the bolometer as indicated by the galvanometer indicated the amount of radiant heat falling on the platinum surface. The interior of the vessel was painted with a dull black paint, which absorbed practically all the radiant heat falling on it, or was silver plated and polished.

Four series of experiments were conducted with mixtures of Cambridge coal gas and air, namely:- 9.8% and 15% in the black walled vessel, and 13% and 15% in the vessel with polished walls. The general conclusions obtained from the experiments in the black walled vessel were as follows:-

1) The total amount of heat lost to the walls of the vessel by radiation up to the time of maximum pressure is approximately proportional to the third power of the maximum absolute temperature, multiplied by the time of the explosion.

2) The total radiant heat lost to the walls during the explosion and the subsequent cooling is about 25% of the heat of combustion of the gas.

3) The emission of radiation at all times varies with the temperature and with the time from ignition.

4) In weak mixtures (and probably also in stronger mixtures) the rate at which radiation is

emitted is a maximum some time before the attainment of maximum pressure, and probably occurs at the time when the flame fills the vessel.

5) Weak mixtures radiate much more powerfully in the initial stages of cooling than do strong mixtures when they have cooled to the same temperature as the weaker.

6) Carbon dioxide emits radiation about twice as strongly as does an equal volume of water vapor at the same temperature.

7) The total heat lost by radiation up to the time of maximum pressure decreases as the initial pressure of the mixture is increased.

8) Denser mixtures radiate heat much more strongly than thinner mixtures, especially at the instant of maximum pressure and in the initial stages of cooling. The emission varies approximately as the square root of the density.

One of David's sets of curves, showing pressure, temperature, total radiation, and radiation per sq. cm. of cylinder area is shown in Fig. 11. The relation of radiation loss in calories per sq. cm. per sec. to the size of the vessel and the initial pressure is shown in Fig. 12. This radiation loss, after correcting for absorption, varies with the temperature nearly in accordance with Planck's formula for a single wave of length 3.6 μ. At high temperatures

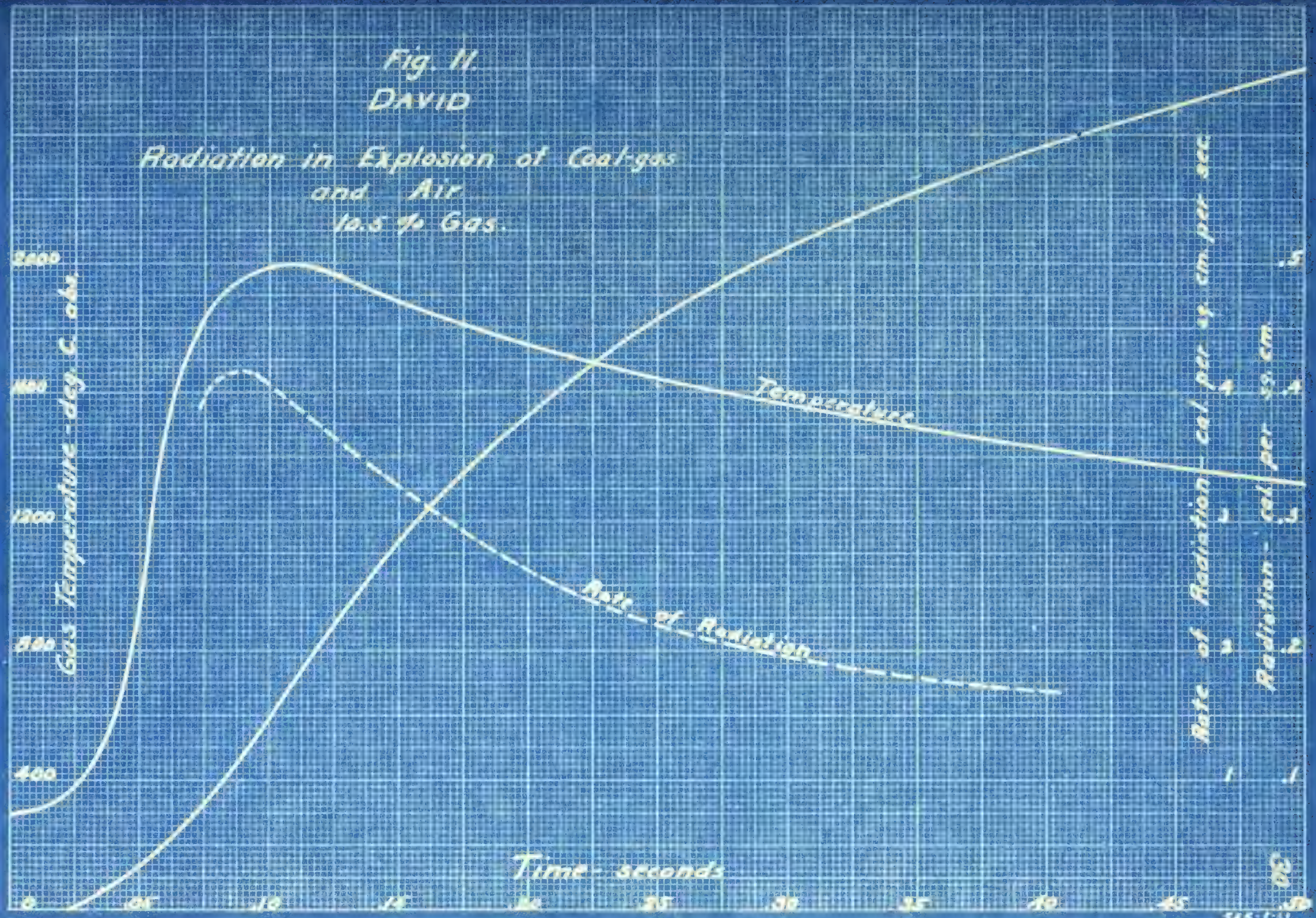
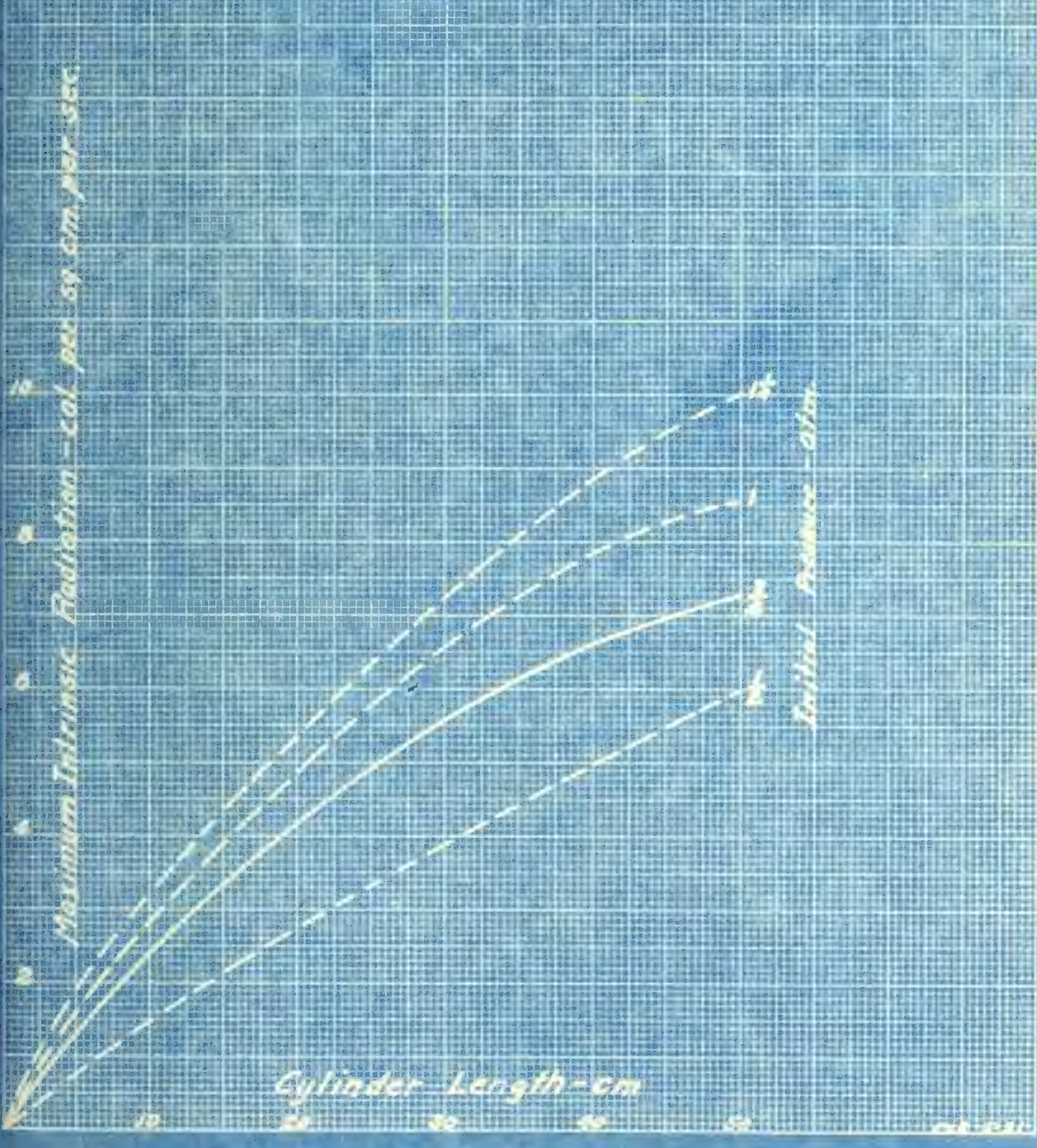


Fig. 11.
DAVID
Radiation in Explosion of Coal-gas
and Air
10.5 % Gas.
Gas Temperature - deg. C. abs.
2400
1600
1200
800
400
Temperature
Rate of Radiation
Rate of Radiation - cal per sq. cm per sec
Radiation - cal per sq. cm
.5
.4
.3
.2
.1
Time - seconds
0
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50

Fig. 12
DAVID
Effect of Initial Pressure & Length
on
Radiation



(1800 to 2400 deg. C.) the Planck formula reduces approximately to a variation with the square of the absolute temperature.

In a later article David discussed the calculation of the results from observed data, and derives the formulas on which the curves given above are based. In another article he discusses the radiation from a mass of burning gas from a theoretical standpoint, and draws various conclusions in regard to the wave length of the radiation emitted, etc.

Effect of CO_2 on the Mixture. Experiments were made in the same apparatus when the mixture was diluted with carbon dioxide instead of the nitrogen of the air. Lower explosion pressures were developed in each case than in the former experiments. David attributes this difference to

1) the greater specific heat of CO_2 at high temperatures.

2) dissociation phenomena, leaving a considerable amount of gas unburned at the time of the maximum pressure.

The theoretical analysis of Appendix I of this discussion confirms these hypotheses.

Conduction. David has recently made experiments to determine the loss of heat to the walls of the explosion vessel by conduction. His original explosion apparatus was used, with the addition of a polished silver grid which was mounted on a piece of linoleum, and placed on the end wall of

the vessel. This grid was connected in a galvanometer circuit in such a way that the deflections of the galvanometer indicated the temperature of the grid, and consequently the conduction loss to the area covered by the grid. The total loss by conduction was taken as the amount of heat used in heating the grid (as indicated by the galvanometer) plus the amount passing through the grid to the linoleum backing. This last amount was calculated from a power series formula with empirical coefficients.

It was found that the loss by conduction varied over different parts of the vessel, and therefore a position was selected for the grid which gave a mean loss over the entire vessel.

The loss of heat up to the time of maximum pressure by conduction, in percent of the heat of combustion of the gas mixture used, is given in the following table:-

Percent gas	Percent loss
15.0	5.1
12.4	5.5
9.7	11.0

The greater time of explosion for the weaker mixtures overbalances the effect of the high temperatures attained in the strong mixtures, and increases the heat loss over that observed for the strong mixtures.

At 0.5 sec. after ignition the 15% mixture has lost by conduction about 38% of its heat of combustion. The 12.4% mixture has at the same time lost about 34% and the 9.7% mix-

ture about 28% of their respective heats of combustion. The curves in Fig. 13 show the rate at which heat loss by conduction is proceeding while cooling is going on. The weaker mixtures in the initial stages of cooling lose heat more rapidly than the stronger mixtures when they have cooled to the same temperature. This is probably due to convection currents, which are more vigorous in the early stages of cooling than in the latter.

No mention is made in David's report of any correction for radiant heat absorbed having been applied to the values obtained from the silver grid experiments. Polished silver absorbs about 4% of the radiant heat falling on it[1], even when highly polished. It is probable that the silver grid actually in use absorbed more than this amount, owing to the deposition of soot on the grid. It therefore appears that David's results should be corrected for this discrepancy.

Miscellaneous.

The experimenters mentioned in the preceding paragraphs have produced the most trustworthy results, so far as the measurements of the physical phenomena involved in the explosions of gaseous mixtures are concerned. A considerable amount of literature has been devoted to the chemical and mathematical sides of the problem, however, and many interesting

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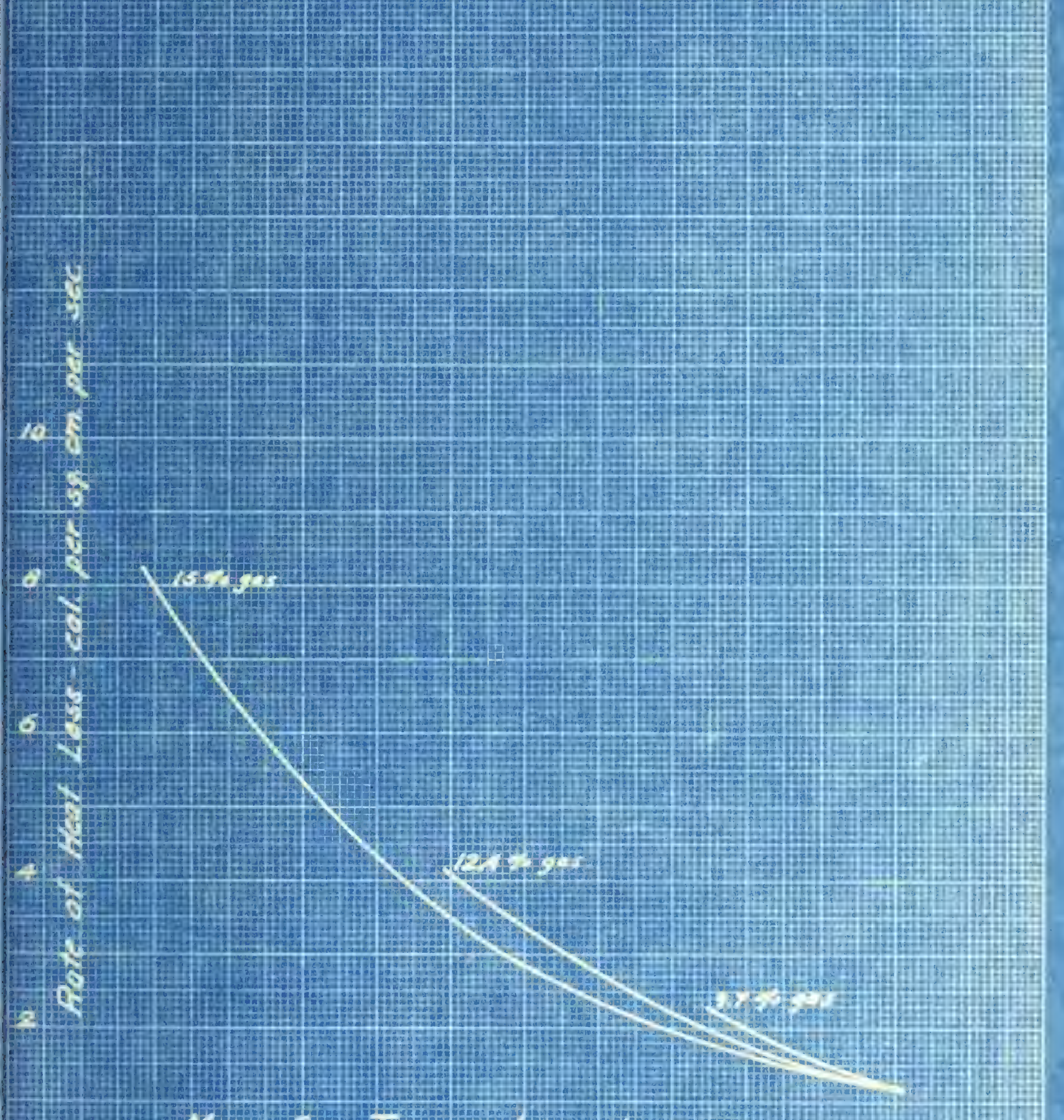
[1] Landolt & Bornstein--Physikalisch-Chemische Tabellen, p. 961.

Fig. 13
DAVID
Heat Loss by Conduction



and important results have been obtained.

A number of other experimental researches along the same lines as those mentioned above are available, among which are those of Pier, Langen, Falk, and Dixon, but their work, for the most part, is merely a confirmation of the results previously discussed.

III. DESCRIPTION OF APPARATUS

The original apparatus was designed and built by Prof. A. P. Kratz during the year 1915. After being used for a number of experiments (1 to 171) work was suspended on the problem until September, 1919, at which time the writer was assigned to the problem.

The apparatus was then reconstructed. Tests 172 to 201 inclusive were made with the apparatus reconstructed substantially as originally built.

The original apparatus consisted of a cast steel base plate with four removable vessels or heads, designed to be bolted to the base plate. The heads were respectively cylindrical, conical, hemispherical, and "L-head" shaped, (patterned after the common L-head gasoline engine cylinder). The actual dimensions and proportions of the heads are shown in Fig. 14. The head selected for use was placed on the base plate, with a thin paper gasket around the rim, and fastened in place by eight 1¼" cap screws. The heads were very heavily built, being designed to withstand safely an explosion pressure of 2500 pounds per square inch. A 4" two bladed fan, driven by a shaft through the center of the base plate, afforded a means of stirring up the mixture

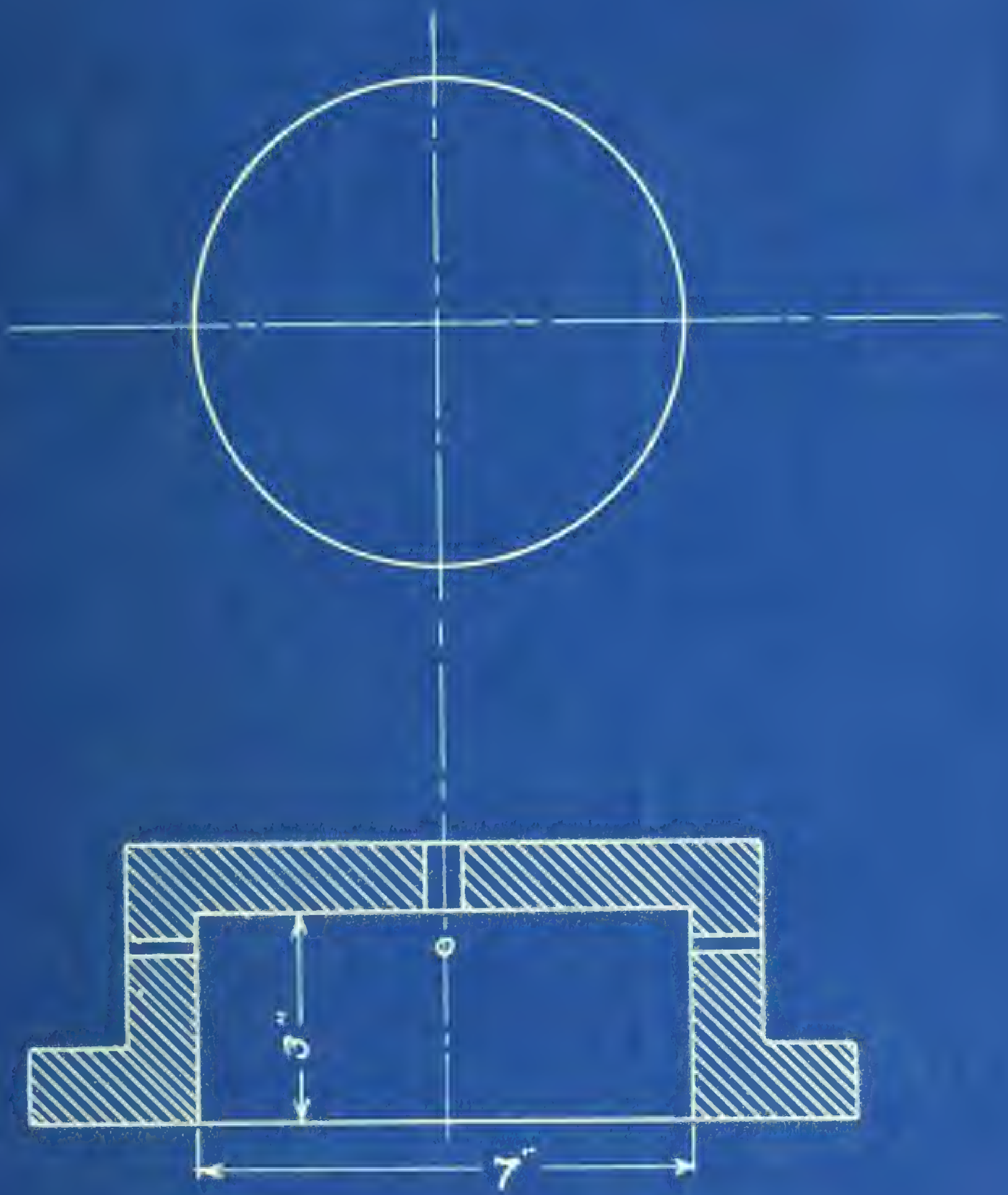


Fig. 14a

Cylindrical Vessel

Volume = 155 cu. in. Superficial Area = 143 sq. in.

Ratio $\frac{\text{Area}}{\text{Vol}}$ = 1.238

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Fig. 14 b.
Conical Vessel

Volume = 155 cu. in. Superficial Area = 116.1 sq. in.

Ratio $\frac{\text{area}}{\text{Vol.}}$ = 0.75

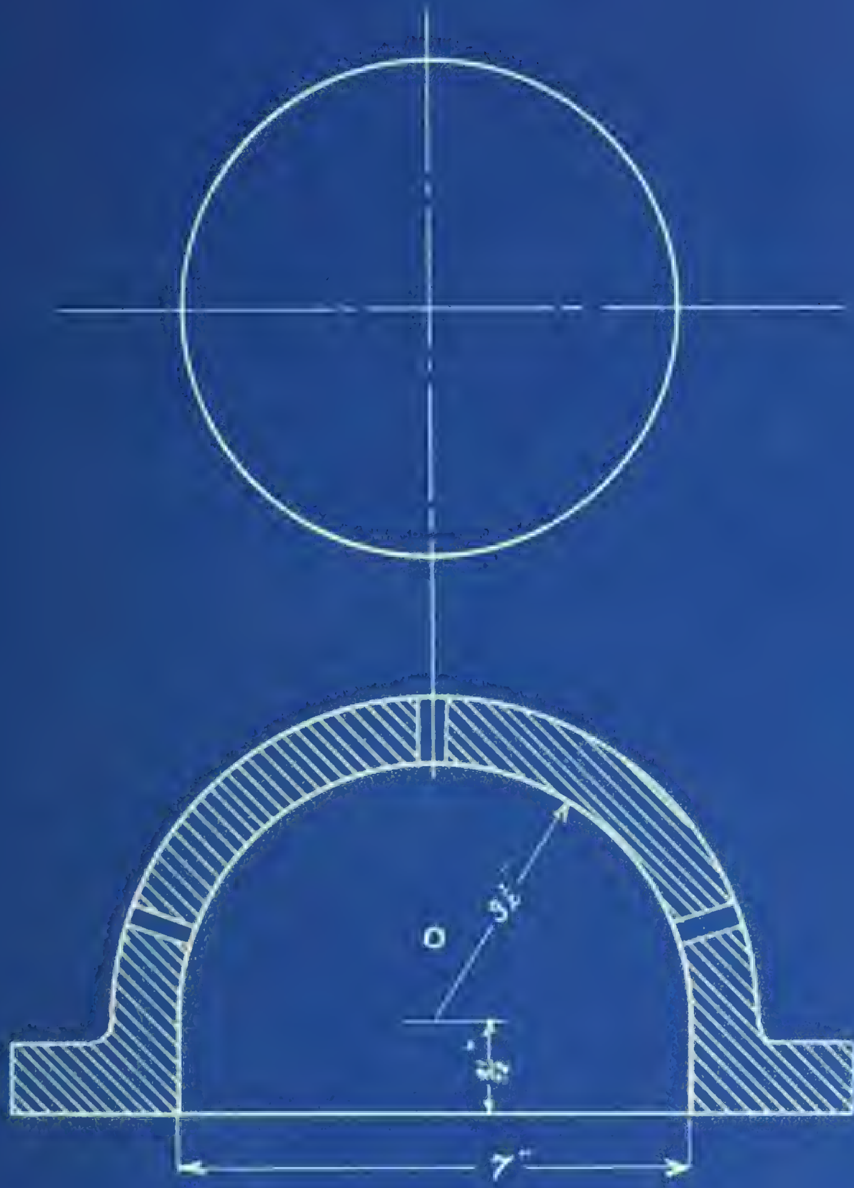
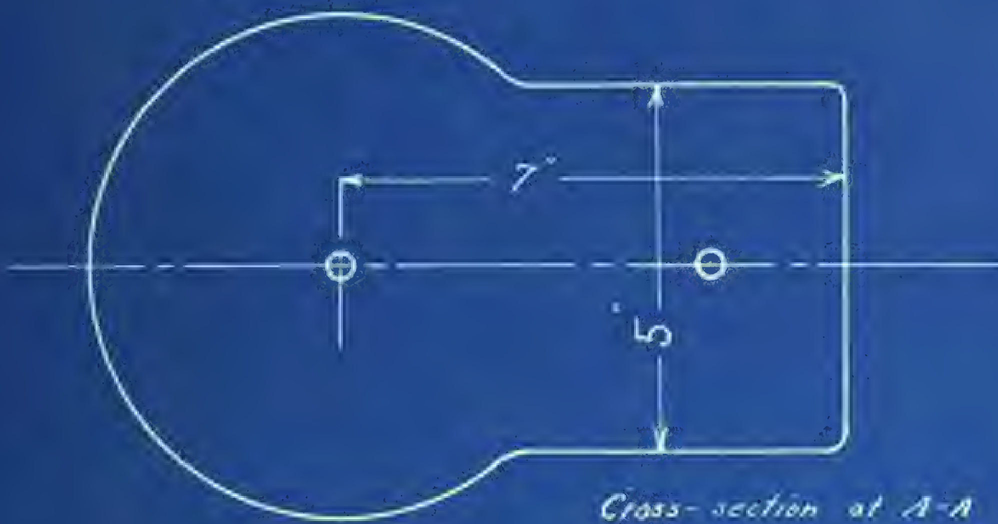


Fig. 14 c.

Hemispherical Vessel

Volume = 155 cu. in. Superficial Area = 81 sq. in.

Ratio $\frac{\text{area}}{\text{Vol}}$ = 0.693



Cross-section at A-A

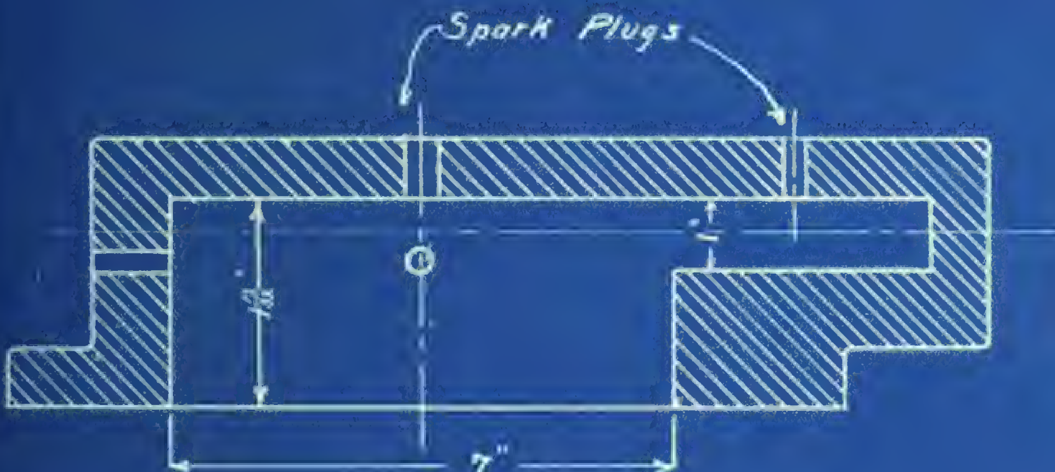


Fig. 14d
"L-Type" Vessel

Volume - 155 cu. in.   Superficial Area = 187 sq. in.

Ratio $\frac{\text{area}}{\text{vol.}}$ = 1.618

before and during explosion. A hole for the ignition plug and holes for intake and exhaust piping, as well as for the indicator, were provided in each head, as shown in Fig. 14.

The indicator, screwed into the side of the head in use, is perhaps the most important part of the apparatus. An optical instrument was adopted as being the only type suitable for use in such an investigation. A drawing of the original indicator is shown in Fig. 15. The diaphragm indicator was adopted as being most accurate and convenient.

The indicator diaphragm, (D) 3/64" thick, and having a semicircular corrugation concentric with the outside circumference of the disc, was cut from a bar of chrome-vanadium steel. The corrugation was introduced in order to insure a straight line calibration for the indicator, to give the diaphragm greater flexibility, and to prevent slippage of the parts when heavily loaded. A small threaded projection at the center of the diaphragm gave a means of connecting the mirror system. A thin steel spring (S), bent at right angles and supported by a small standard (R) screwed to the base bar (B) was joined rigidly to the diaphragm by two small clamp nuts on the threaded projection (P). A small piece (approximately 1/16" in diameter) of concave mirror (M) was cemented to the spring (S) at such a distance from the support as was found by trial to give a proper deflection. A small enclosed arc lamp projected a beam of light on the mirror, whence it was reflected to the photographic paper, held on a longitudi-

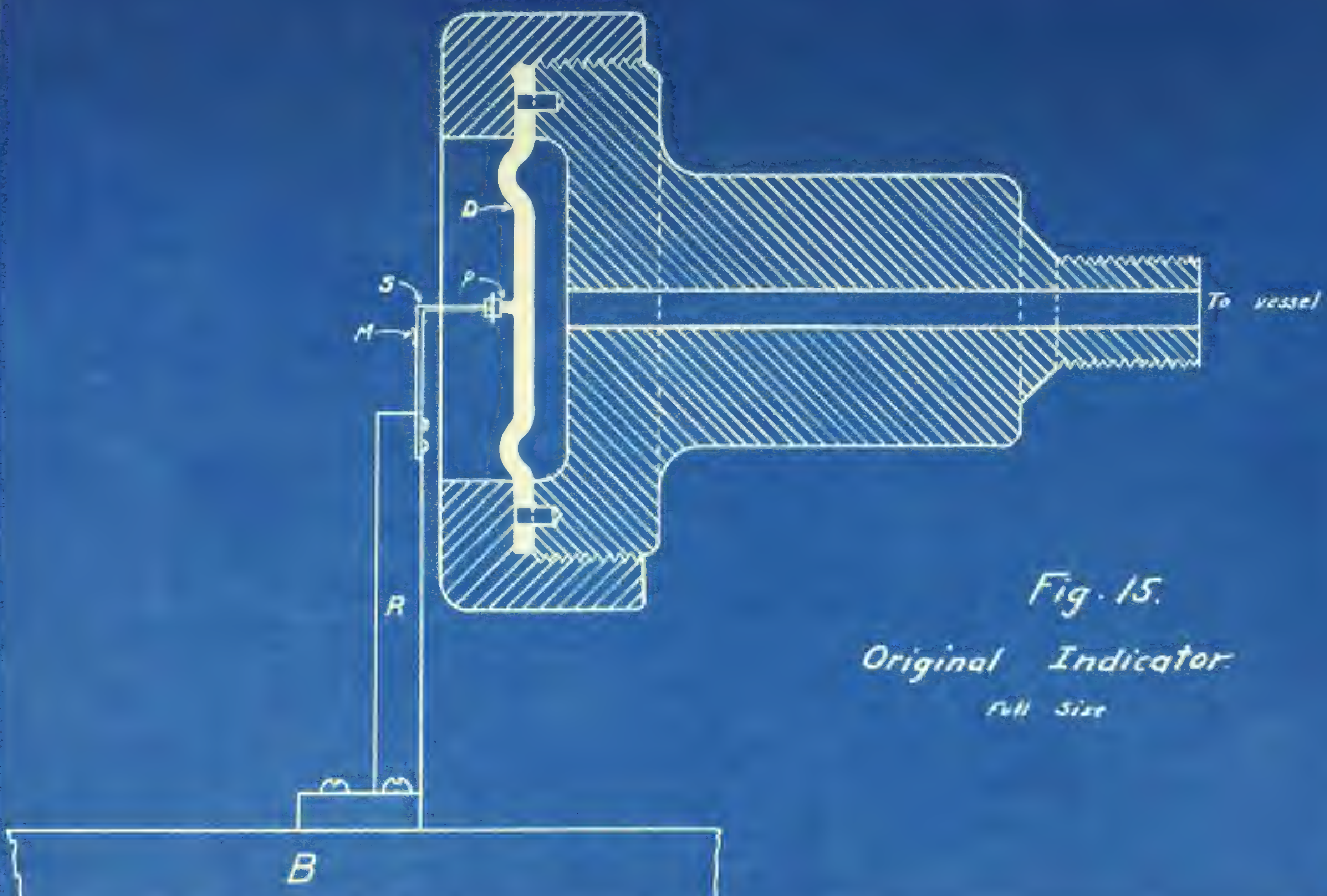


Fig. 15.

Original Indicator

Full Size

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nally moving slide. The arc lamp and slide were placed at proper distances from the mirror to give a clear-cut image of the crater of the arc on the photographic paper, which gave a narrow black line for the record. The mirror used was a small piece cut from a concave galvanometer mirror of 1 meter radius of curvature.

This indicator gave very satisfactory results when adjusted, but was very inconvenient to adjust, as the mirror could not be moved to give the proper position of the spot of light on the photographic paper. The indicator was also affected by any vibrations occurring in the heavy base bar (B). The vibration of heavy machinery in the building made these vibrations very noticeable in the base and explosion lines. The indicator was therefore remodeled as will be described later.

The explosion vessels had two connections diametrically opposite for the admission and exhaustion of the air and gas. Heavy steel needle valves, made from solid bars, were used to open or close the ports for admission or exhaustion.

Gas and Air Measurement

The gas used in all the experiments, except some few tests with hydrogen, was illuminating gas, taken directly from the city mains. A storage tank of 10 cu. ft. capacity was filled with the gas, and several complete series of explosions made with the same tankful. In this way a constant

gas composition was insured, except as the unavoidable deterioration of the gas occurred. The gas was stored over water, and hence was saturated in all experiments.

The scheme originally employed to secure the desired mixture of gas and air and to introduce the mixture into the vessel was that of measuring the partial pressures of the gas and air. A mercury manometer (Fig. 16) fitted with a special electrical contact device, and reading to 0.01", was connected to the gas and air piping system for measuring these partial pressures. The accuracy of measurement attained with the electrical contact on the manometer insured a maximum error of 0.05% in the air gas ratio.

Ignition.

Ignition was accomplished by means of a ¾" induction coil supplied with current from a 6 volt storage battery. For some few explosions ignition was effected by an Atwater-Kent Unisparker, driven slowly by the apparatus controlling the motion of the slide for the photographic paper. The Unisparker, however, proved rather unsatisfactory at these low speeds, as it often failed to fire the charge, and was therefore discarded, and the induction coil again used. A contact fixed on the slide carrying the paper closed the induction coil circuit at a time to give ignition at the desired point on the photographic record. A mica insulated spark plug with a 0.03" gap, communicated the spark to the charge. A small spark gap, in series with the plug, was placed close to the photo-

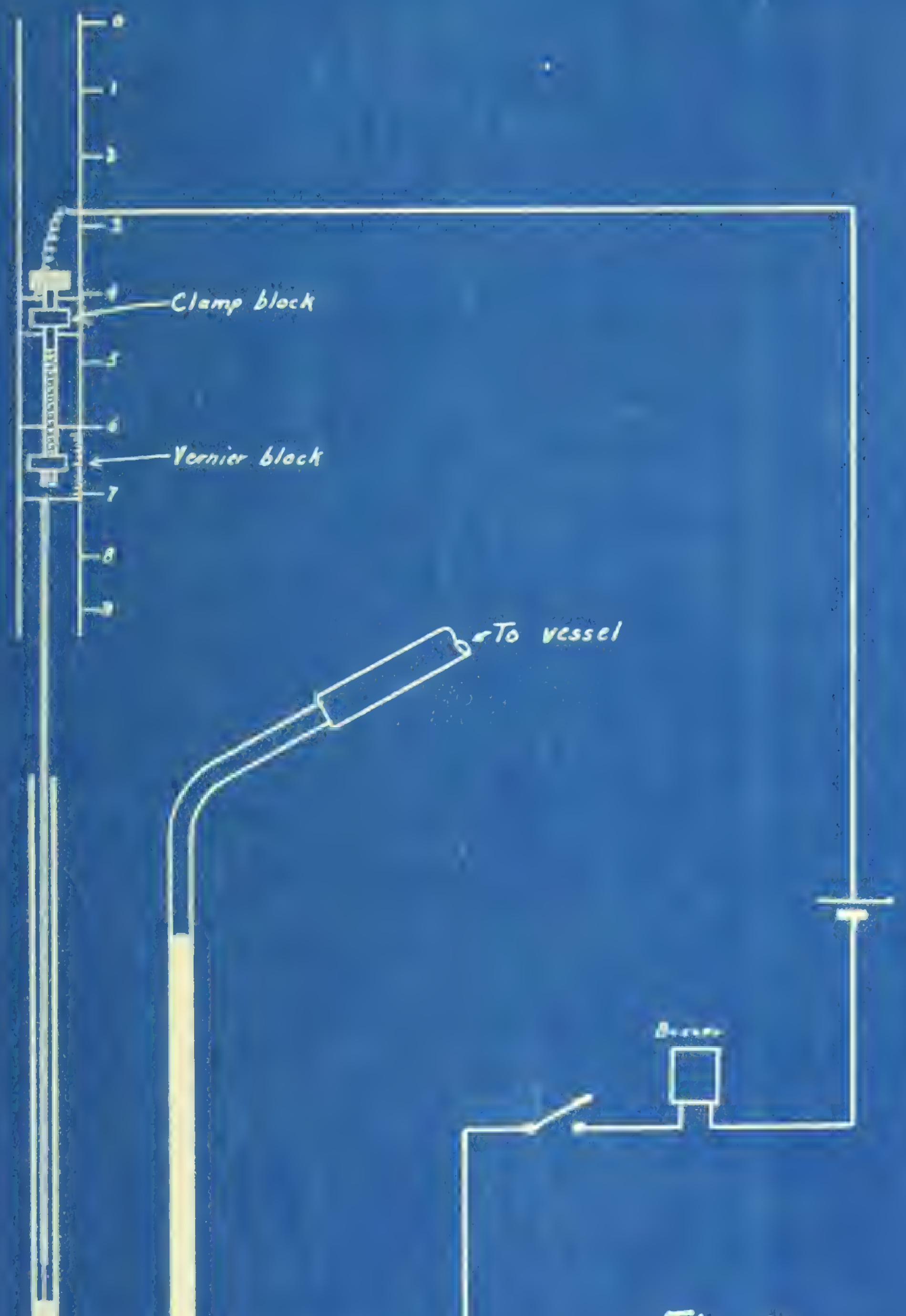

Fig. 16

Mercury Manometer

graphic paper on the moving slide. The passage of the spark across this gap, and at the same instant across the plug in the vessel, gave a dot on the photographic paper. By measuring the horizontal distance from this dot to the perpendicular erected from the base line through the position of the spot of light from the indicator when at rest, and laying off this distance on each explosion card, the exact time at which the spark passed, with reference to the beginning of the rise of pressure, could be determined. Usually from 6 to 10 separate discharges occurred while the slide contact remained closed. These discharges occupied a time of about 0.1 sec.

Paper Motion.

The photographic paper was mounted on a slide (S) which moved longitudinally in a frame bolted to the base bar (B) (Fig. 17). The slide was given its motion by a "constant speed" device, similar to that used on vertical blue printing machines. The speed of this device was not constant, and hence the time scale of the diagram was somewhat distorted. As the slide, having considerable inertia, required an appreciable time to attain the speed set by the constant speed device. This defect was remedied when the apparatus was remodeled.

Time Record.

A record of time was obtained from an electrically driven tuning fork mounted close to the indicator. A small concave mirror cemented to one leg of the fork received a beam of light from the arc lamp, and reflected it to the photo-

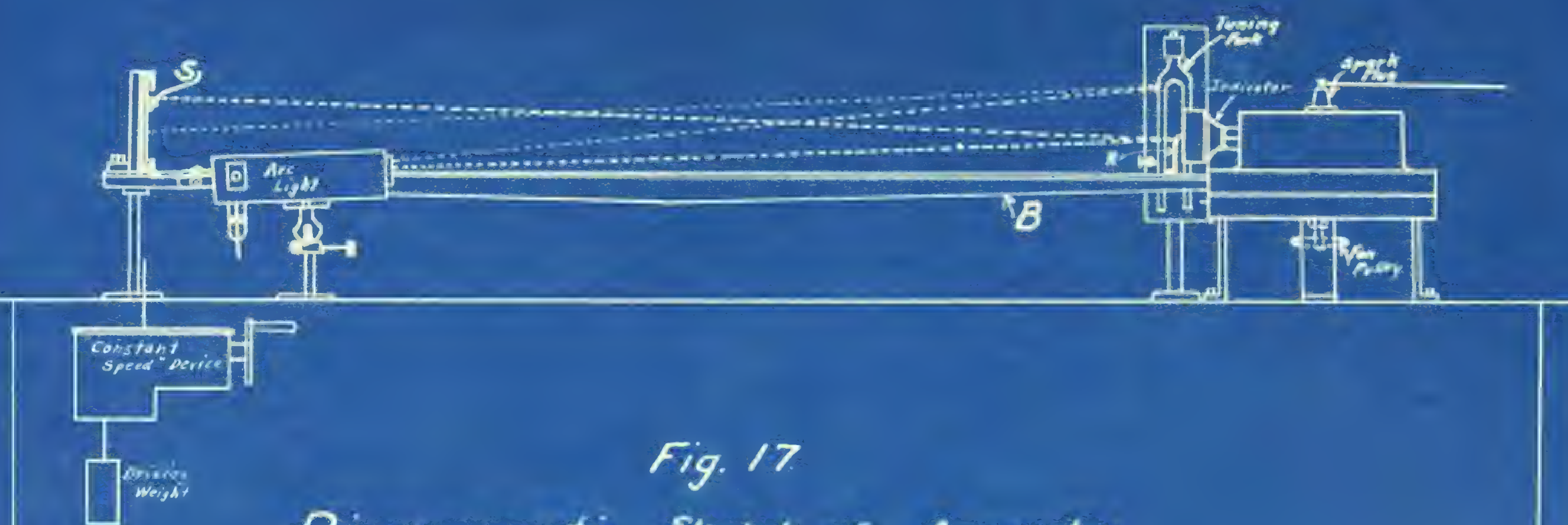

Fig. 17
Diagrammatic Sketch of Apparatus

graphic paper, tracing a wave with a frequency of 100 vibrations per second on the paper when the fork was in vibration.

The method of calculating the time of explosion from this record will be illustrated later.

Recording Paper.

The photographic paper originally used was Eastman P. M. C. bromide paper, cut into strips 2" x 11". Later it was found advisable to use a special Eastman recording paper (known as "Eastman Recording Paper No. 1"). This paper was coated with an emulsion very nearly as fast as the standard Kodak film emulsion, and good results were obtained.

The photographic records were developed immediately after taking them in the standard MQ developer recommended by the Eastman Kodak company.

New Apparatus.

The apparatus as originally built was remodeled in 1919-1920 and some new features added. The principal change effected was in the design of the indicator. The heavy base bar (B) was removed entirely, and the spring carrying the mirror was clamped directly to the indicator body. A small strut communicated the motion of the diaphragm to the spring. A set of two concentric rings formed the base to which the spring was clamped. These rings could be turned to any desired position and clamped, thus giving a range of adjustment of the plane of motion of the indicator mirror to any desired angle. Vertical adjustment was provided for by the use of

long studs to which the mirror spring was clamped. Photographic views of the indicator as remodeled are shown in Fig. 18.

This instrument proved to be very satisfactory, since it was free from all effects due to vibrations and jars, and had ample opportunity for adjustmemt. The indicator was calibrated by comparison with a special dead weight tester connected in the air line to the explosion vessel. A high pressure air reservoir, carrying 500 lb. per sq. in., provided a source of high pressures for calibration. The instrument was calibrated when screwed into place on the explosion vessel, and no adjustment of it was made during any series of experiments. The calibration was checked several times during each series, and from the results obtained from the calibrations, it is evident that the instrument retains its adjustment and calibration characteristics for long periods of time. A sample calibration curve is shown in Fig. 19.

It appears from certain mathematical calculations as to the natural period of vibration of the indicator that the instrument easily followed the most rapid explosion occurring in any of the work done in this investigation.

The paper motion was also remodeled. The longitudinally moving slide was discarded, and a revolving drum 11" in circumference was substituted. The drum was driven through a worm gear reduction by a small D. C. motor, which was capable of being regulated to a speed proper for the explosion record to be taken. A contact attached on the circumference

Fig. 18. Photograph of

New Indicator.

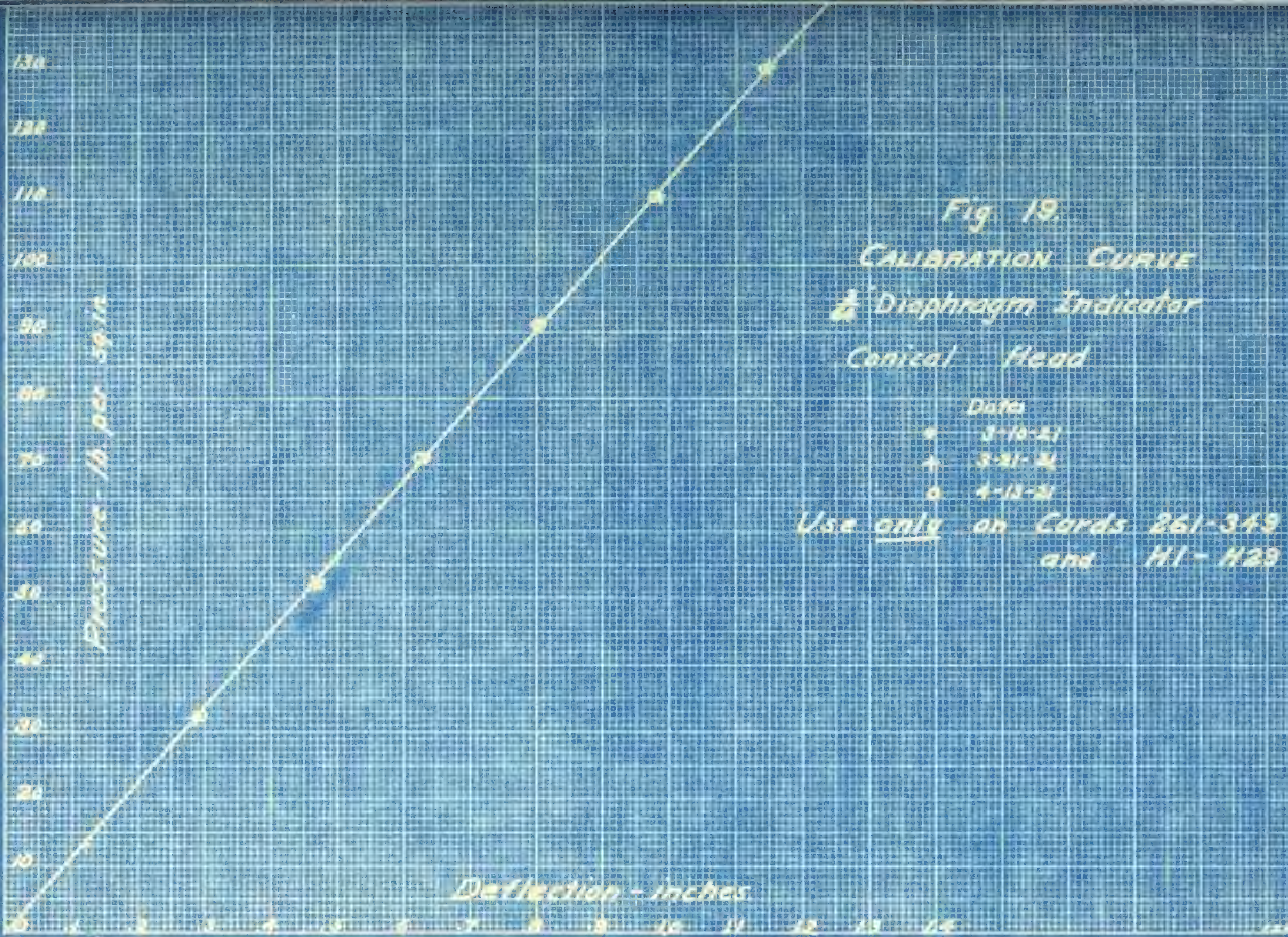
Fig. 19.
CALIBRATION CURVE
Diaphragm Indicator
Conical Head
Data
Use only on Cards 261-349
and H1-H29
Pressure - lb. per sq. in.
Deflection - inches

of the drum completed the primary circuit of the induction coil to give ignition at the proper position of the drum.

This drum motion was much more satisfactory than the slide which was formerly used. The drum could be started some time before making the explosion, the firing switch could then be closed, and the card taken with the drum running at a constant speed.

The method of measuring the gas to be admitted to the explosion vessel was changed. A 100 cc. gas burette, graduated to 0.1 cc. was connected to the gas line and to the explosion vessel. The volume of gas required to give any desired air-gas ratio was calculated from the volume of the vessel and the piping through which the gas was admitted, and proper corrections were made for changes of partial pressure, etc. This method was more accurate than the partial pressure method of securing the desired mixture. Some minor changes were also made in the gas and air piping.

The new apparatus proved to be exceedingly convenient and reliable, and the greater part of the results herein given were obtained with it. A photograph of the complete apparatus is shown in Fig. 20 and a detailed photograph of the conical explosion vessel with all connections is shown in Fig. 21.

The gas and air piping is illustrated in Fig. 22 and the wiring diagram for the ignition system in Fig. 23.

Fig. 20. General View of Explosion Apparatus

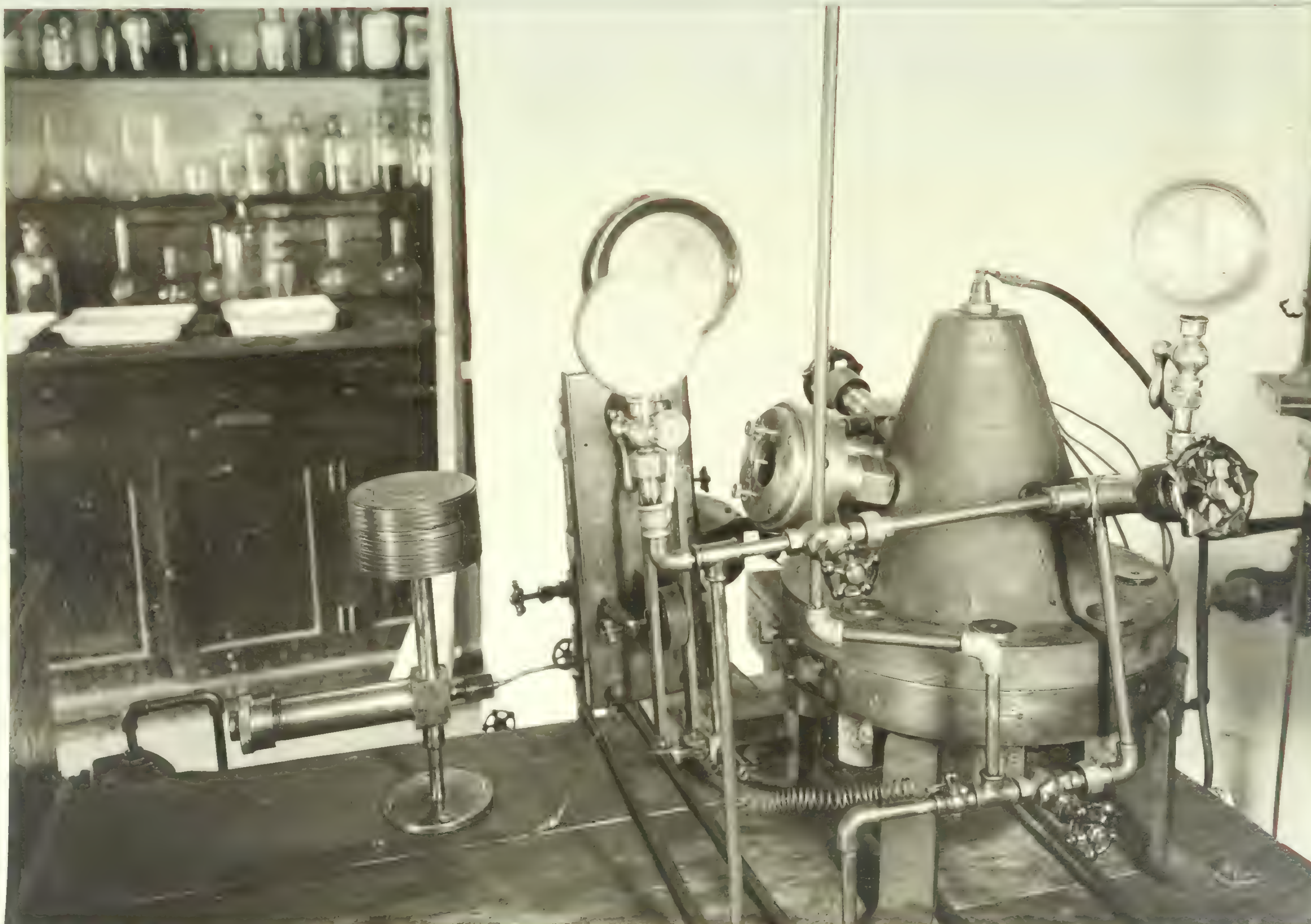

Fig. 21. View of Conical Explosion Vessel.

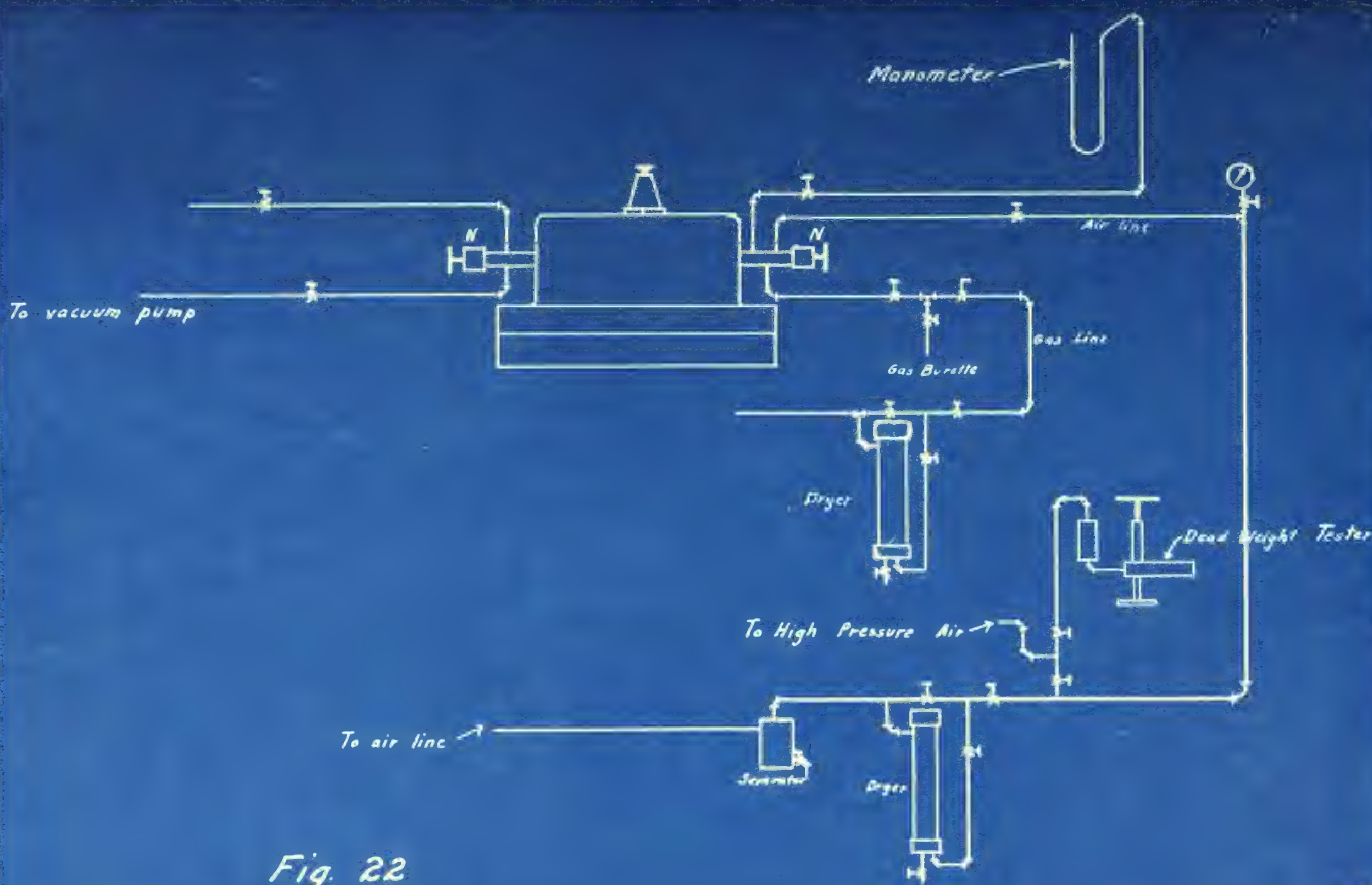

Fig. 22

Gas and Air Piping

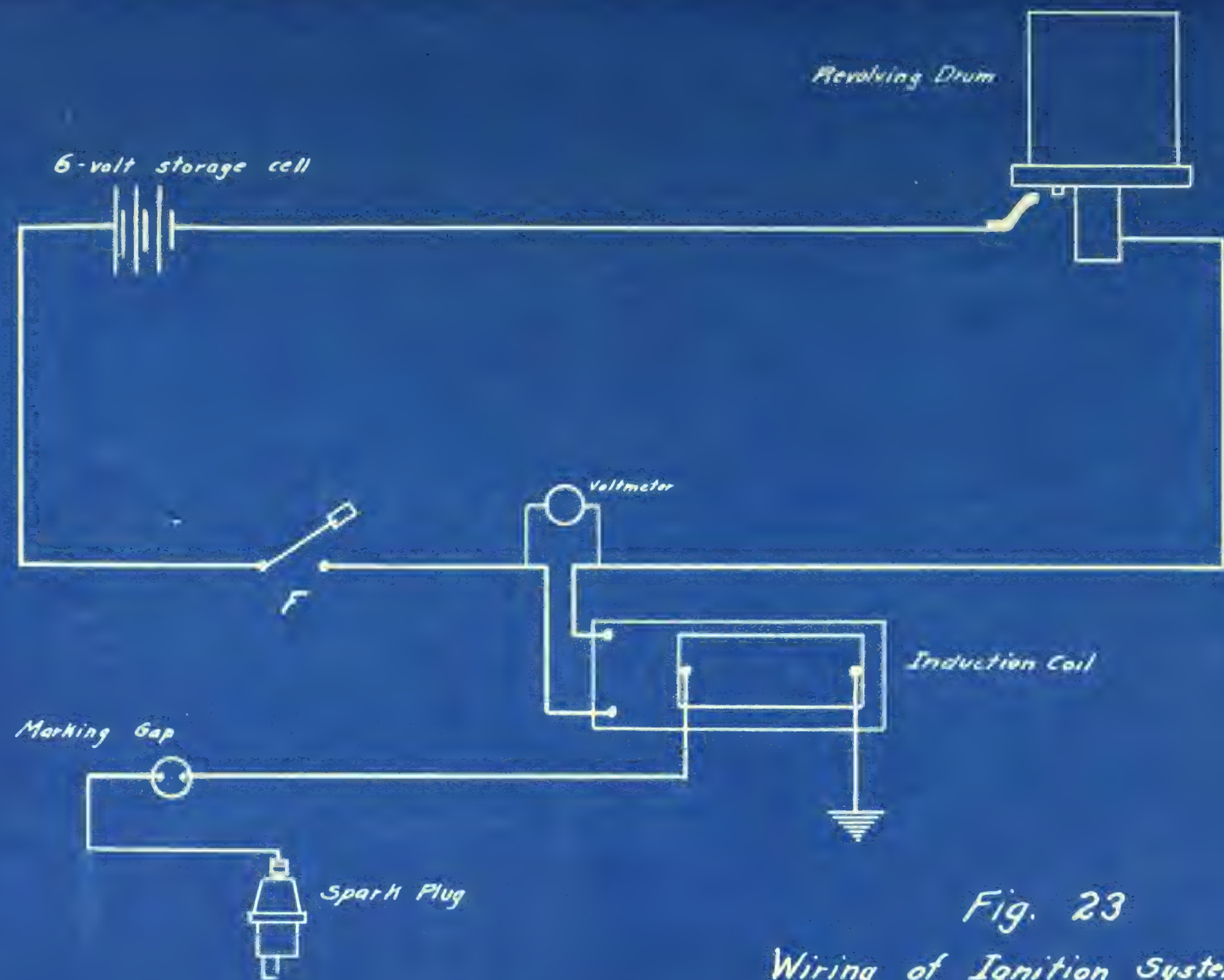

Fig. 23
Wiring of Ignition System

IV. PROCEDURE IN MAKING AN EXPLOSION

Before any explosions were made in a new series of tests, a considerable amount of gas was blown out through the supply pipes to insure a fresh supply to the vessel. The vessel was then thoroughly swept out with compressed air, during which time the fan was kept running. After three or four minutes, the air was shut off, the exhaust valve (E) (Fig. 22) was closed, the vacuum pump started, and the vessel exhausted to about 10" of mercury absolute pressure. After shutting off the vacuum pump, the gas was measured in from the burette as desired. When the proper volume of gas had been admitted, the exhaust valve was opened, and air filled the vessel and piping up to atmospheric pressure. The needle valves (N) were then closed, and the desired mixture of gas and air in the vessel was ready for explosion.

In case the partial pressure method of obtaining the desired mixture was employed, the procedure was modified somewhat. The zero reading of the manometer was recorded, and the platinum contact point (P) (Fig. 16) was set, by means of the vernier, at a position to give the desired partial pressure of the air. The vessel was then evacuated until the mercury in the manometer fell below the contact point. Air

was permitted to leak in slowly until the buzzer in the manometer circuit indicated that the proper partial pressure of the air had been reached. The gas valve was then opened, and gas was admitted until atmospheric pressure was obtained in the vessel.

The fan in the vessel was run about 600 rpm. during the admission of the gas (except as specially noted) in order to insure thorough mixing of the charge. It was also run during explosion for certain series of tests.

After placing the photographic paper on the drum and starting the driving motor, the arc light was started and a zero (or atmospheric) pressure line traced on the paper. The tuning fork was then set in vibration, the shutter in front of the paper was opened, and the firing switch (F) (Fig. 23) was closed. At the next closing of the contact on the drum, the primary circuit of the induction coil was completed, the spark was passed in the cylinder, and the charge fired. The photographic record was then removed and developed as previously described.

Determination of Maximum Pressure and Time of Explosion.

Fig. 24 is a reproduction of an actual explosion card, with the necessary lines and dimensions for determining the maximum explosion pressure and the time of explosion.

The line A-A is the zero, or atmospheric pressure line traced before explosion. OP is a perpendicular to this zero line, passing through the highest point on the pressure

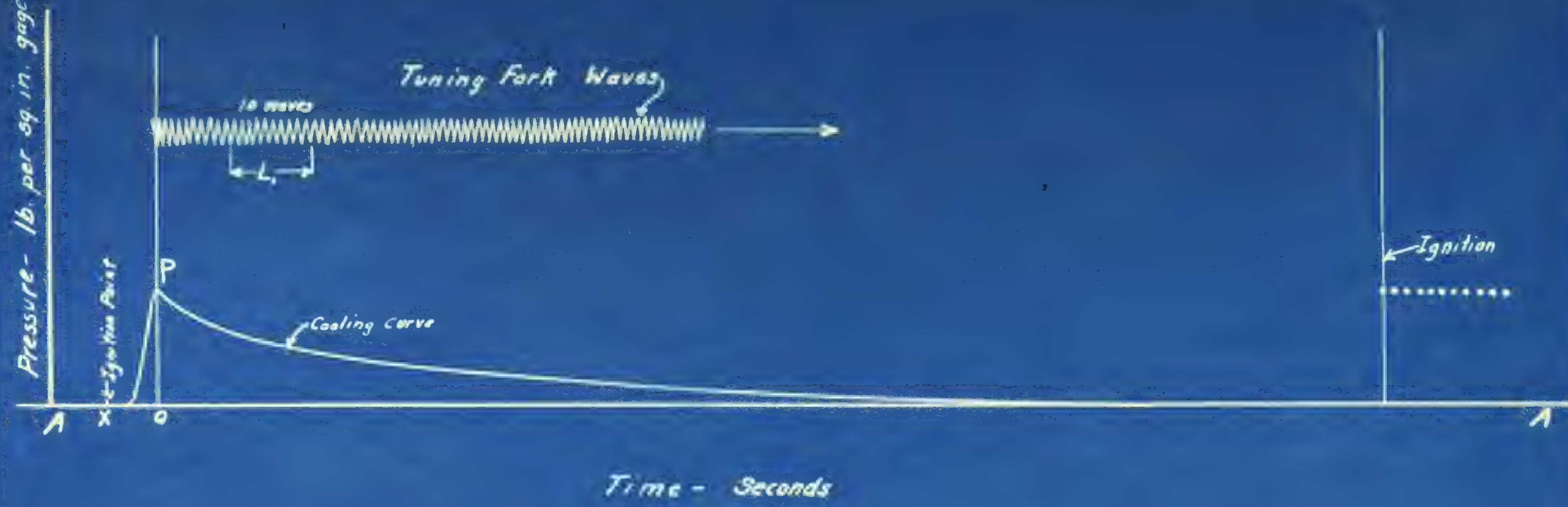

Fig. 24
Facsimile of Explosion Indicator Card.

Card No 322.

Initial Pressure - Atmospheric.

Maximum Pressure = 82.5 lb. per sq. in.

Time of Explosion = 0.054 second.

Air-Gas Ratio = 6

Initial Temperature - 75°F.

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curve. The distance OP then represents the maximum pressure developed by the explosion, and by reference to the calibration curve (one of which is shown in Fig. 19) the actual pressure in pounds per square inch may be determined. The dots at the right hand end of the card were produced by the small series spark gap, placed close to the paper. The dot at the left of the group marks the first spark passed in the vessel. A certain distance (obtained by measurement on the drum itself) is laid off from this dot, parallel to the zero pressure line, giving the point X as the ignition point. The horizontal distance XO is then a measure of the time of explosion.

The sine wave traced by the tuning fork is situated along the top of the card. The tuning fork used had an actual rate of vibration (by calibration) of 98 vibrations per second.

The following notation is used in connection with the determination of the time of explosion.

N_1 = an arbitrary number of vibrations, usually 10.

N_s = number of vibrations of fork per second.

N = number of vibrations of fork contained in the distance L (which is equal to XO).

L = XO (representing the time of explosion).

L_1 = horizontal distance covered by N_1 vibrations of the fork.

T = the time of explosion in seconds.

Then

$$N = TN_s \qquad \text{and } T = \frac{N}{N_s}$$

$$\frac{L}{L_1} = \frac{N}{N_1} \quad \text{and} \quad N = \frac{L}{L_1} N_s$$

Then

$$T = \frac{L\ N_1}{L_1 N_s}$$

If N_1 is taken as 10 vibrations and N_s is 98 vibrations per second,

$$T = \frac{10}{98} \frac{L}{L_1} = 0.102 \frac{L}{L_1}$$

Hence by measuring L and L_1, and proceeding with the above calculations, the time of explosion may be determined as accurately as the measurement of the various distances can be made.

V. RESULTS

General.

All the results of this investigation were obtained from explosions made with illuminating gas and air. The gas was taken directly from the city mains. Owing to the fact that the experiments on the "L-head" vessel and some experiments on the cylindrical vessel were made in 1915, and explosions were made in the rest of the heads in 1921, a considerable difference existed between the analyses of the gas used at the two different periods. A set of gas analyses follows:

Analysis October 8, 1915.*

CO_2	1.8%
O_2	2.0
CO	21.6
CH_4	17.0
H_2	40.9
Illuminants . . .	7.5
N_2	9.2
	100.0

Approximate heating value: 453 Btu. per cu. ft.

---

* This analysis is approximate only.

Analysis November 13, 1920.

CO_2	7.5%
O_2	0.9
CO	10.5
C_2H_2.	3.4
C_2H_4.	3.4
C_6H_6.	6.2
C_2H_6.	16.6
CH_4	4.7
H_3	23.4
N_2	23.4

Approximate heating value: 787 Btu. per cu. ft.

From a comparison of the approximate heating values of the two samples of gas it is evident that a considerable difference may exist between explosions run with the different lots of gas. The 1915 gas was much richer in hydrogen than the 1921 gas, and hence had a higher rate of inflammation. The gas was stored over water in all cases, and hence was saturated in the the tests made.

Summary of Results on Different Heads.

The method of procedure in testing any one of the heads was to run several series of explosions, under various conditions of ignition, turbulence, etc. Each series consisted of a number of explosions made with different mixtures of gas and air, ranging from the richest to the leanest mixture that could be exploded. No attempt was made to determine accurately the limits of inflammability of the gas, but the mixtures were varied until the mixture denoted by the next "half unit" higher or lower in the air gas ratio failed

to explode.

Curves of maximum pressure and time of explosion plotted against air-gas ratio are given for each different head, and under several different conditions for each head.

An index of the series of tests follows.

Series	Vessel	Number
1	Cylindrical	1
2	L-head	2
3	"	"
4	"	"
5	"	"
6	"	"
7	"	"
8	Cylindrical	1
9	"	"
10	Conical	3
11	"	"
12	"	"
13	"	"
14	Hemispherical	4

Explosions of hydrogen and air were also made in the conical vessel for the purpose of obtaining a check on a method of calculating the explosion pressure. These explosions will be discussed separately.

Series 1.

This series was run on the cylindrical head, with ignition at the center and flush with the upper surface of the vessel. The gas was admitted without stirring and was exploded after standing five or ten minutes.

The curves (Fig. 25) are typical of all experiments

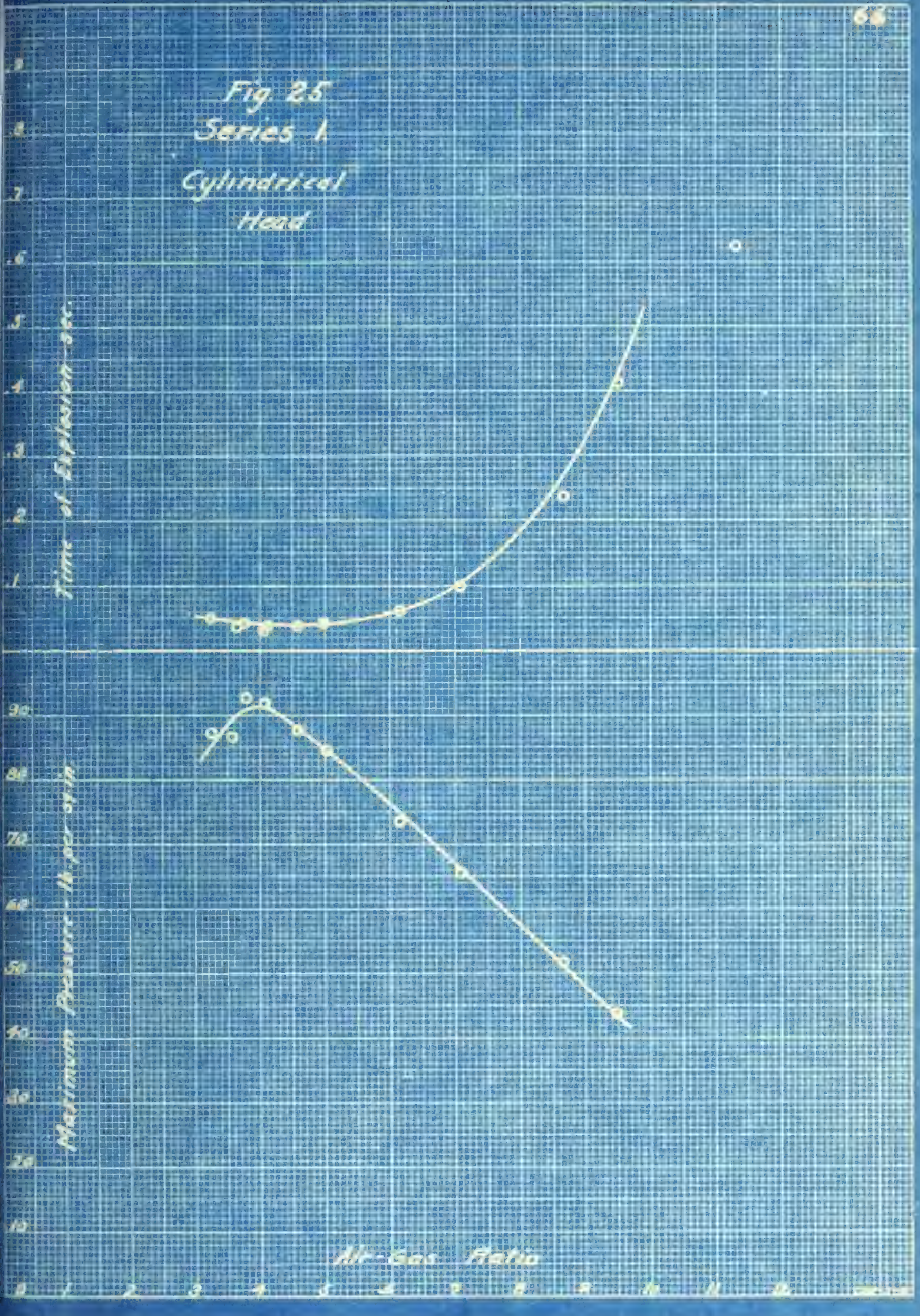


Fig. 25
Series 1.
Cylindrical
Head
Time of Explosion - sec.
Maximum Pressure - lb. per sq. in.
Air-Gas Ratio
.9
.8
.7
.6
.5
.4
.3
.2
.1
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12

of this sort. The air-gas ratio giving the highest explosion pressure is 3.9 to 1, a value considerably less than the theoretical ratio (about 6 to 1). This is accounted for by the fact that the large amount of neutral gases present when a 6 to 1 mixture is fired keep down the maximum pressure much below the value obtained when insufficient oxygen is present. The point at an air-gas ratio of 11.34 is very probably in error on account of the difficulty of measuring the low deflections of the indicator, and on account of the fact that no well defined maximum pressure occurs for the explosion of so lean a mixture. (See Fig. 2).

The maximum pressure developed in this series was 92.5 lb. per sq. in. gage, a value checking rather closely with Clerk's value of 91.0 lb. per sq. in. for an explosion of Oldham gas and air. The time of explosion was practically the same as in the determinations of Clerk, namely about 0.05 second.

Series 2.

This series (Fig. 16) was run on the L-head vessel, with ignition flush with the upper surface of the vessel and at the center of the main chamber. No stirring at any time was used.

As compared with Series 1, in the cylindrical head, the advantage of the former is apparent. The decrease of maximum pressure with the L-head vessel is due to the greater surface exposed to the hot gases during explosion, and to the

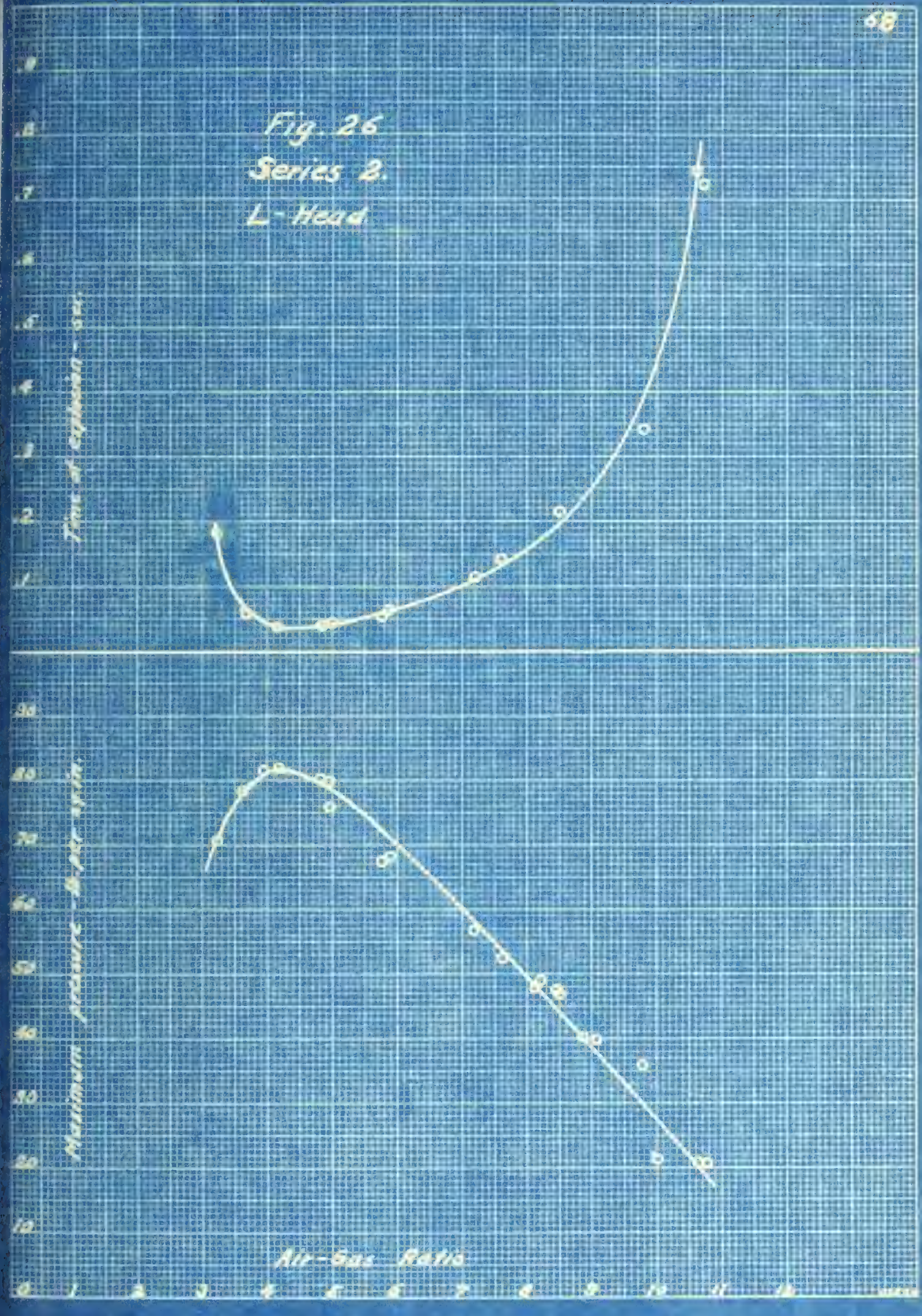


Fig. 26
Series 2.
L-Head
Time of explosion - sec.
Maximum pressure - lb. per sq. in.
Air-Gas Ratio

fact that the time of explosion is shorter in the cylindrical head by about 0.01 sec., thus reducing the opportunity for heat loss.

It is possible that complete combustion does not take place in the L-head vessel when ignition occurs in the main chamber, as the flame may be checked and cooled considerably by passing into the narrow opening of the valve chamber.

Series 2 and 3.

Series 3 (Fig. 27) was run under the same conditions as Series 2, except that the fan in the vessel was run during explosion. A comparison of Series 2 and 3 is shown in Fig. 28.

The higher explosion pressures and the shorter times of explosion produced in Series 3 are very noticeable, especially with the leaner mixtures. The turbulence occasioned by the fan brings the inflammable gas in contact with the air much more rapidly and thoroughly than in Series 2, where no stirring was employed. The higher rate of inflammation in Series 3 reduces the heat loss during the time of explosion, and hence a higher maximum pressure is produced.

Series 4 and 5.

Series 4 and 5 (Figs. 29 and 30) were run on the L-head vessel, ignition occurring at the center of the valve chamber, and flush with the upper surface of the vessel. For Series 4 no stirring of the mixture was used, and for Series 5 the mixture was stirred during explosion.

An increase of maximum pressure is attained by the

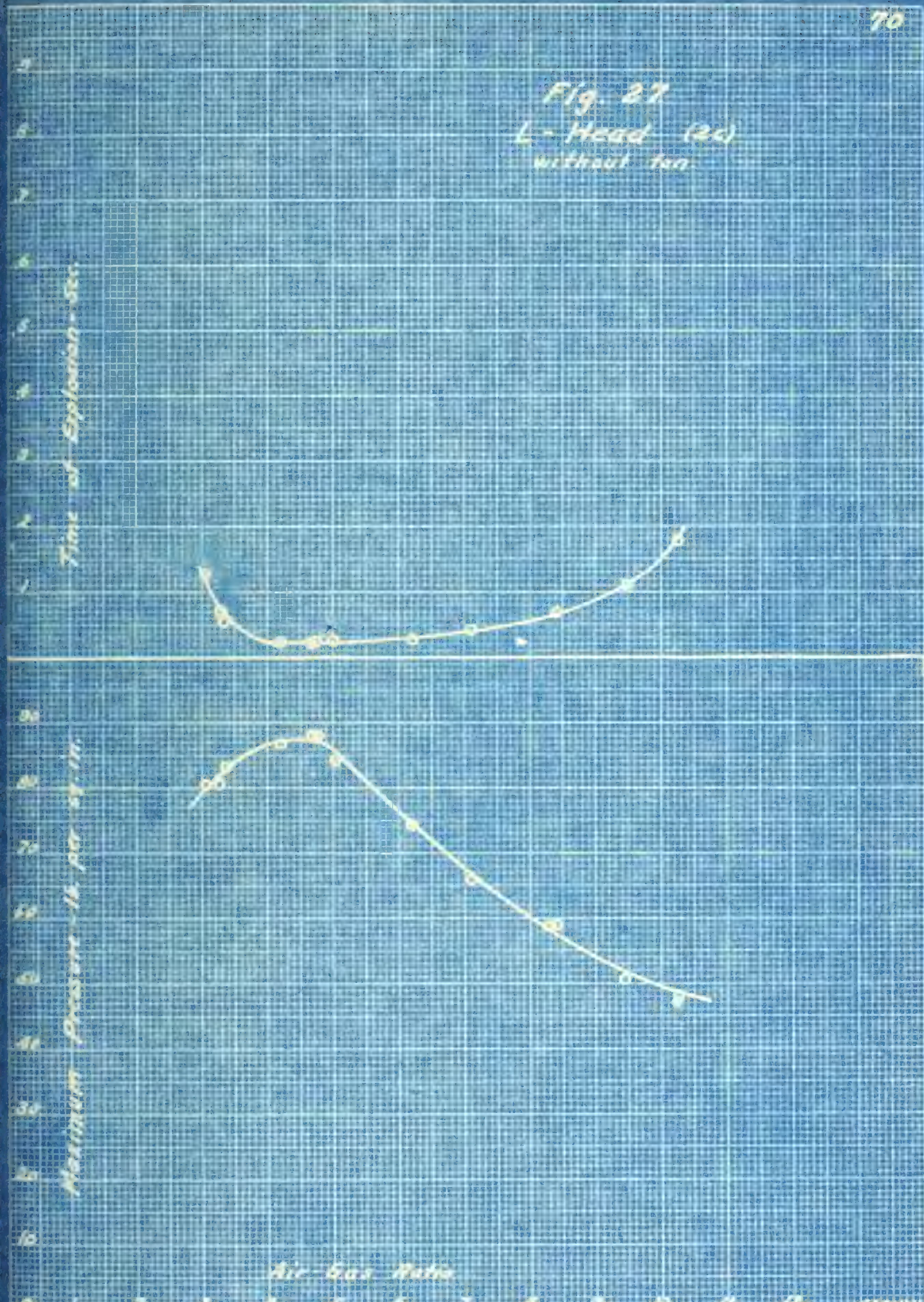


Fig. 27
L-Head (2c)
without fan.

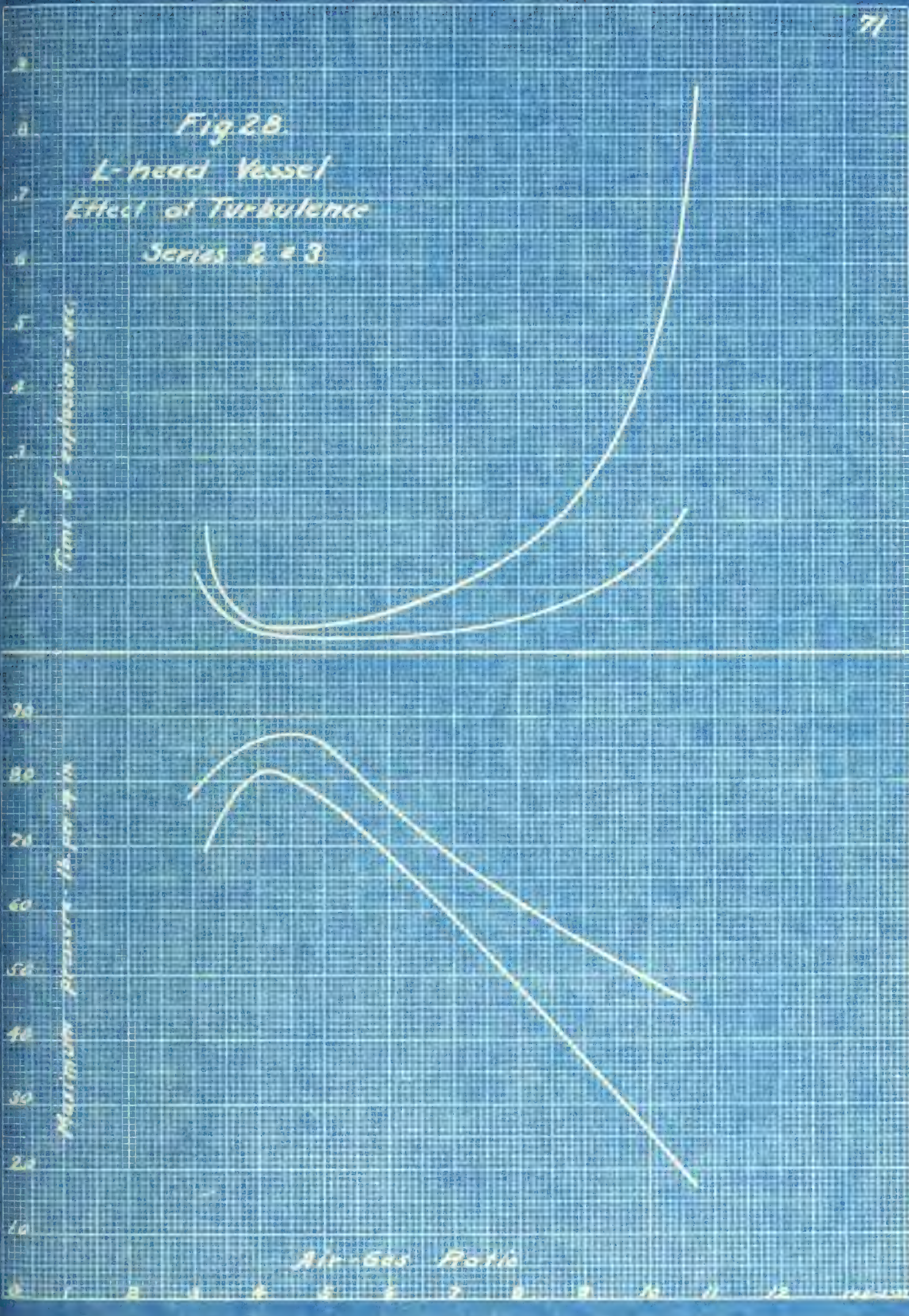


Fig. 28.
L-head Vessel
Effect of Turbulence
Series 2 & 3.
Time of Explosion - sec.
Maximum Pressure lb. per sq. in.
Air-Gas Ratio

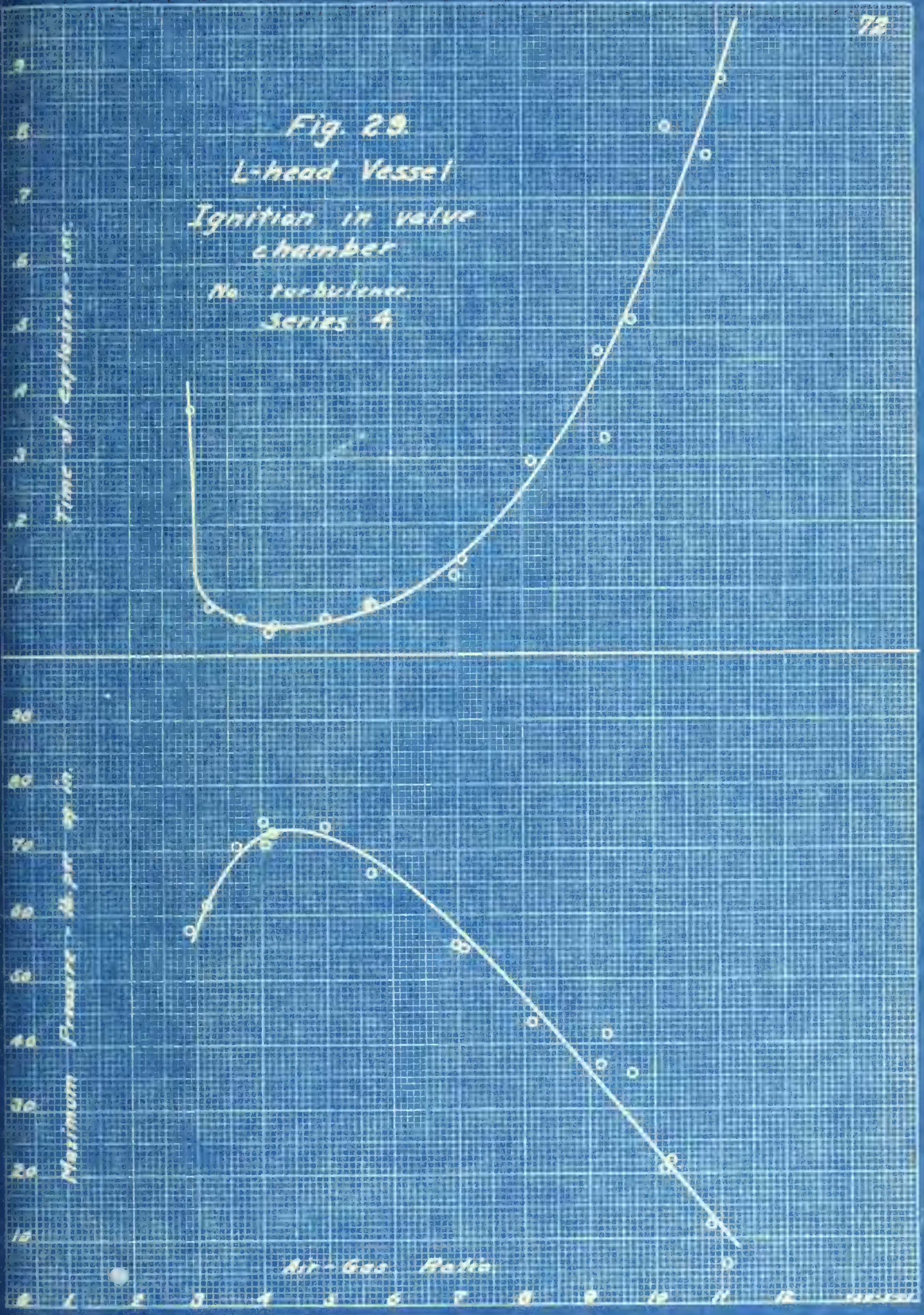


Fig. 29.
L-head Vessel
Ignition in valve chamber
No turbulence
Series 4.

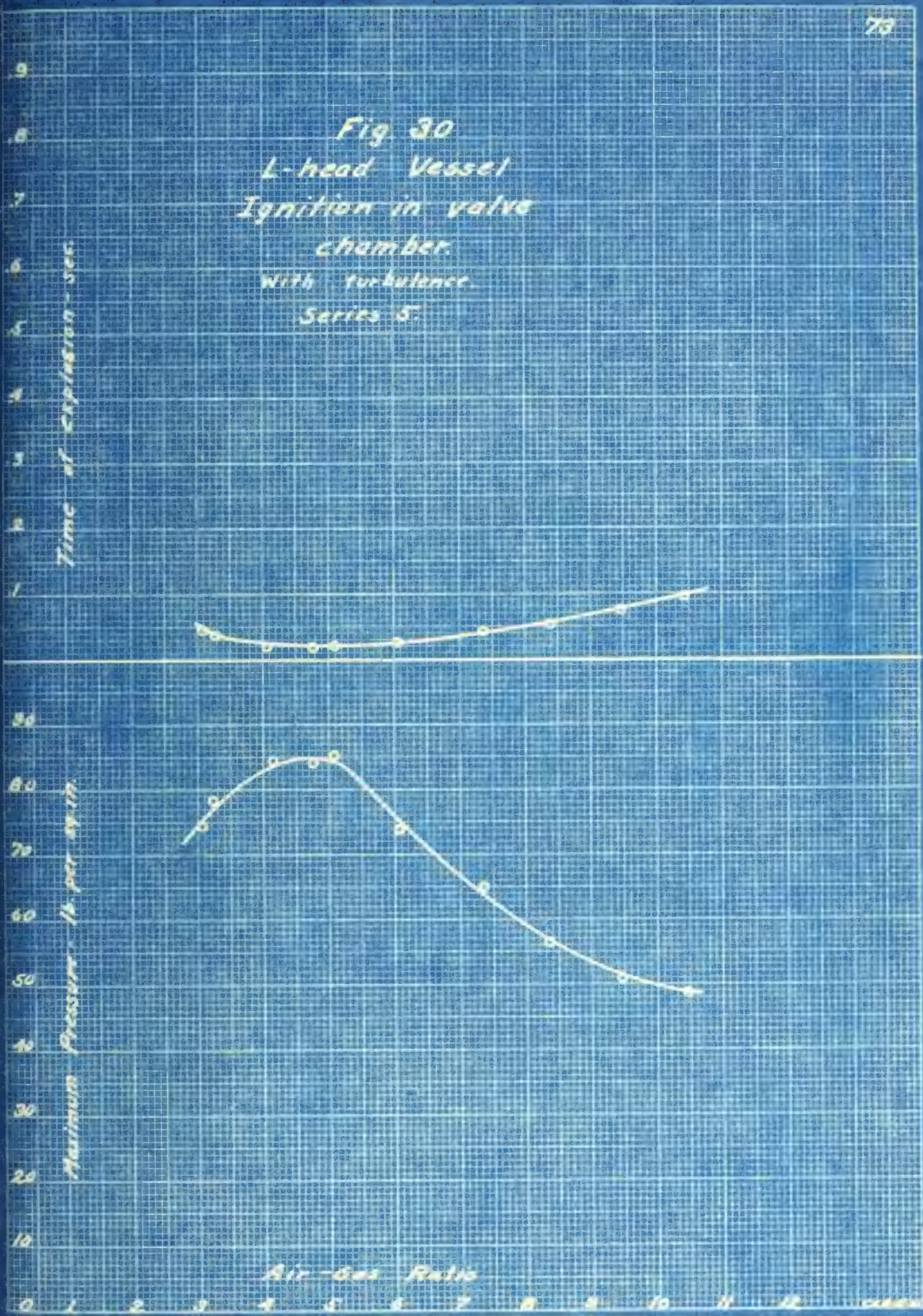


Fig. 30
L-head Vessel
Ignition in valve chamber
with turbulence
Series 5.
Time of Explosion - Sec.
Maximum Pressure lb. per sq. in.
Air-Gas Ratio
.9
.8
.7
.6
.5
.4
.3
.2
.1
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12

use of the fan during explosion, as may be seen from Fig. 31. The influance of turbulence of the mixture during the explosion period in producing a shorter time of explosion is very evident, especially with the leaner mixtures.

Series 6 and 7.

These series were run under the same conditions as Series 4 and 5, except that ignition was produced simultaneously in the main chamber and in the valve chamber (the two spark plugs being placed in series).

The same general form of curves (Figs 32 and 33) were obtained from this series as from Series 4 and 5. The difference in the times of explosion with and without the fan running is very noticeable, especially with the leaner mixtures. This is due to the action of the fan in producing a more intimate mixture of the gas and air molecules. As the mixture approaches more closely the theoretical air-gas ratio ($6\frac{1}{2}$ or 8 to 1) the effect of stirring the mixture in producing a more intimate mixture is not so evident, and the times of explosion with and without stirring approach each other more closely. The pressure curves also approach each other more closely at mixtures near the theoretical, showing that the

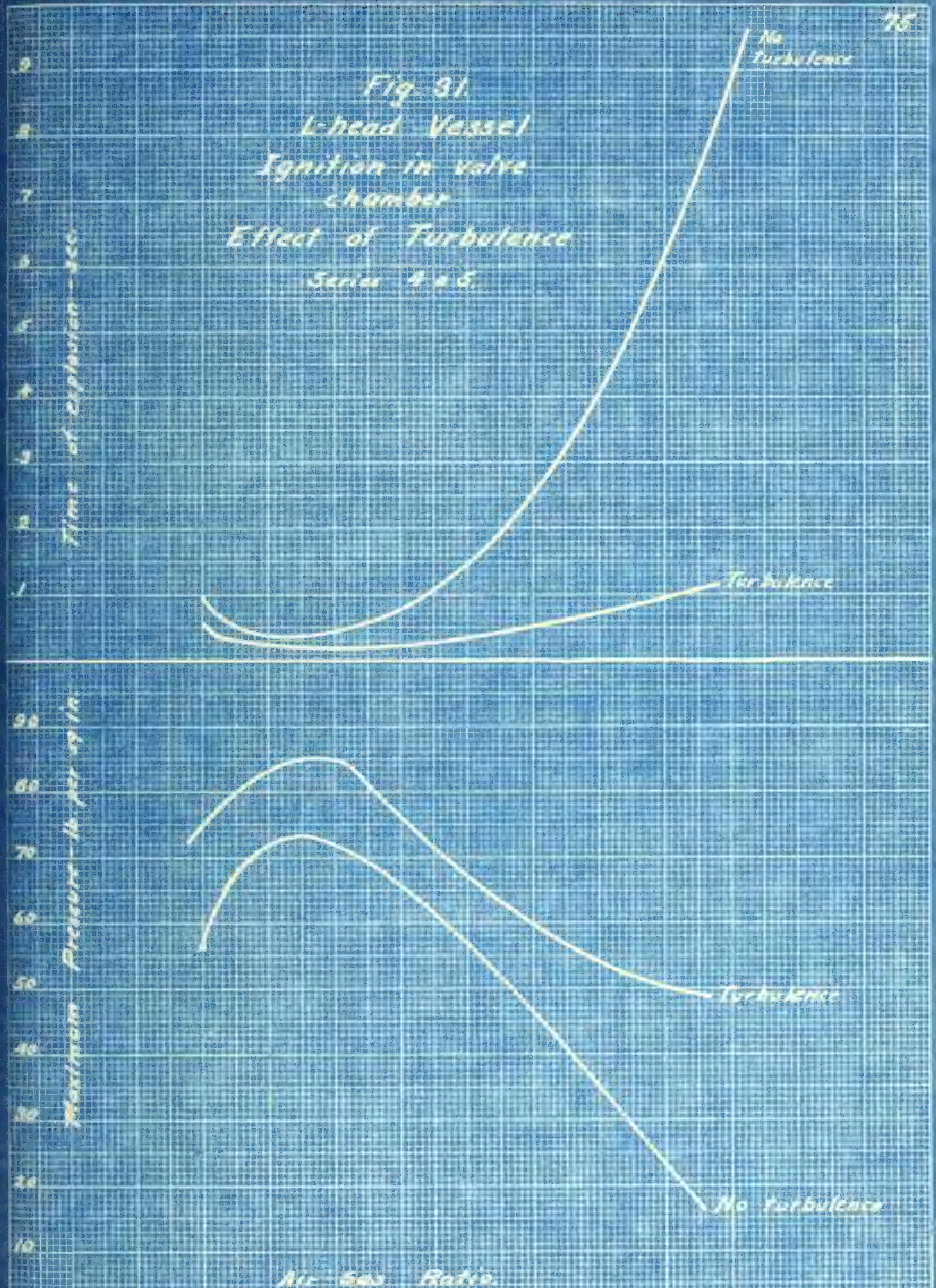


Fig 31.
L-head Vessel
Ignition in valve chamber
Effect of Turbulence
Series 4 & 5.
Time of explosion — sec
Maximum Pressure — lb. per sq. in.
Air-Gas Ratio
No turbulence
Turbulence
Turbulence
No turbulence

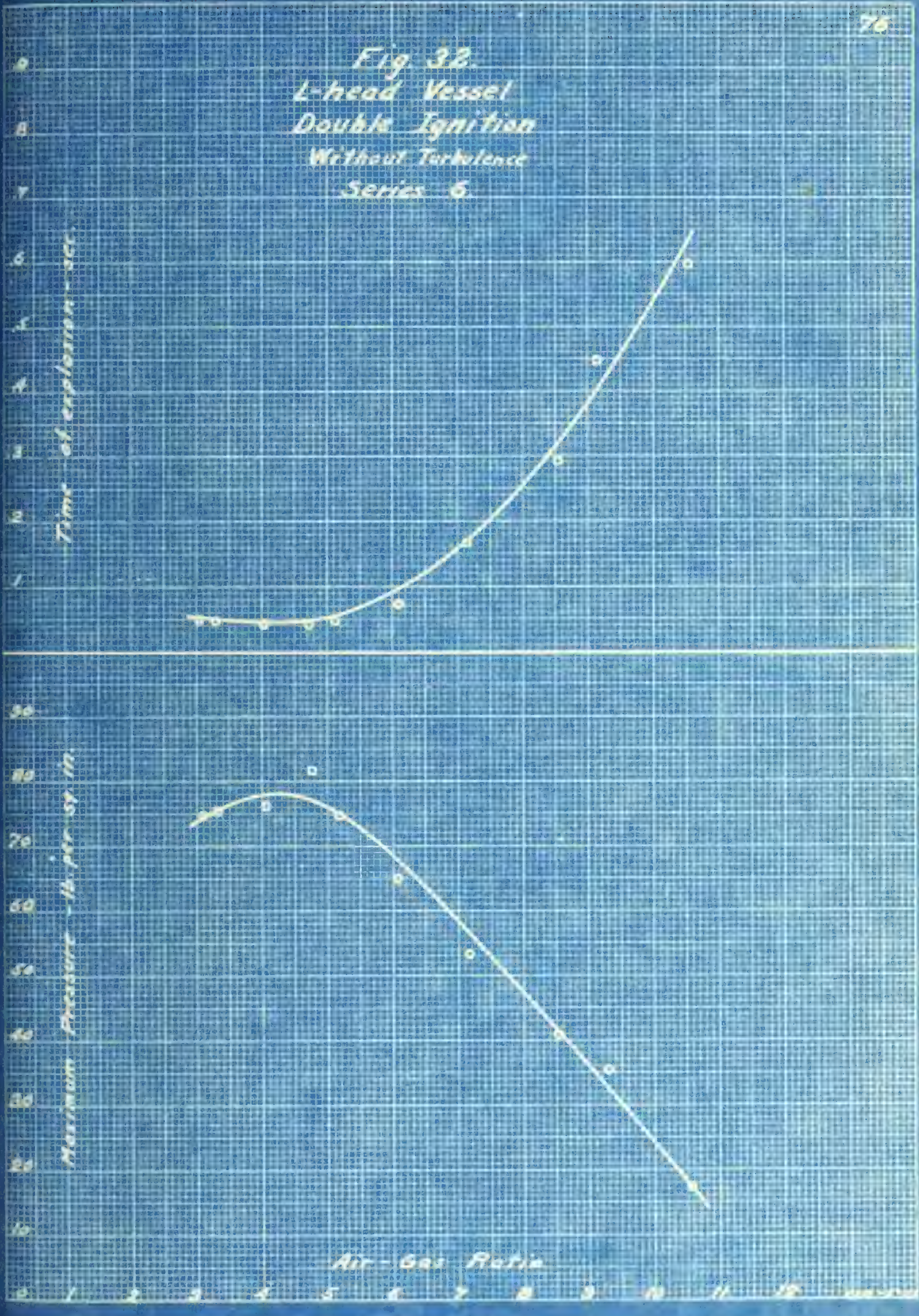


Fig. 32.
L-head Vessel
Double Ignition
Without Turbulence
Series 6.
Time of explosion - sec.
Maximum Pressure - lb. per sq. in.
Air - Gas Ratio
.9
.8
.7
.6
.5
.4
.3
.2
.1
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12

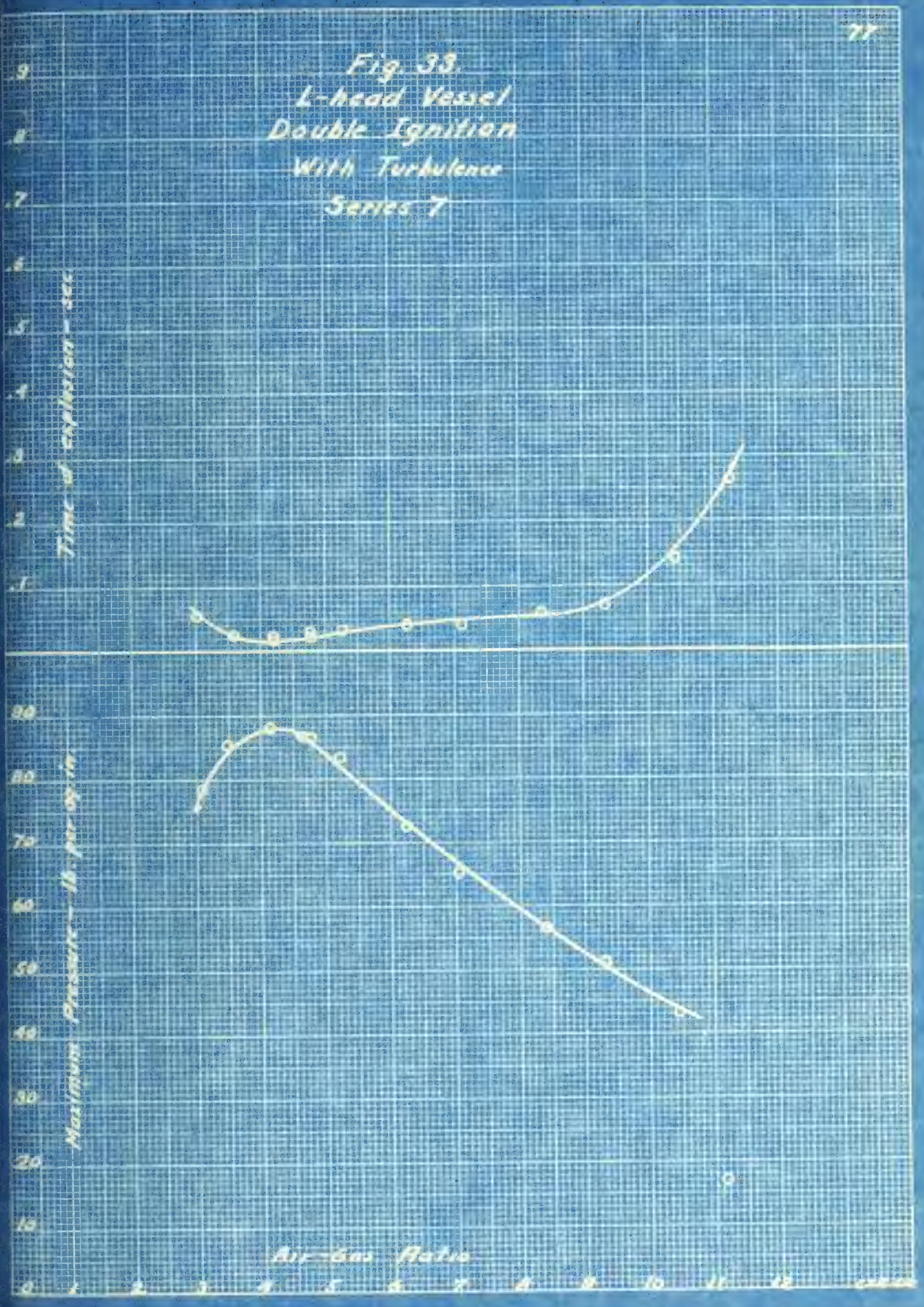


Fig. 33.
L-head Vessel
Double Ignition
With Turbulence
Series 7
Time of explosion - sec.
Maximum pressure - lb. per sq. in.
Air-Gas Ratio
.9
.8
.7
.6
.5
.4
.3
.2
.1
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12

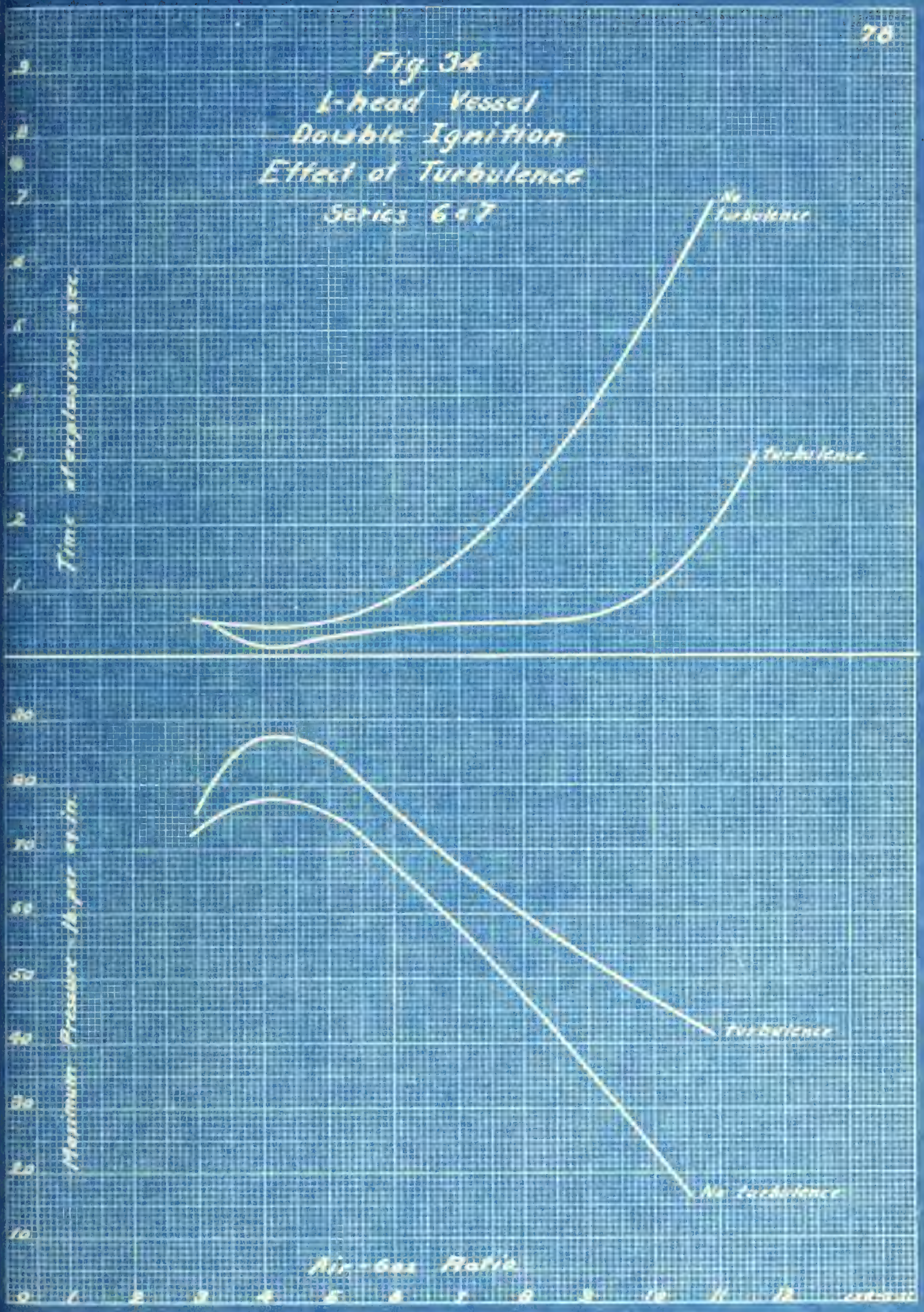


Fig. 34
L-head Vessel
Double Ignition
Effect of Turbulence
Series 6 & 7
Time of explosion - sec.
Maximum Pressure - lb. per sq. in.
No turbulence
Turbulence
Turbulence
No turbulence
Air-Gas Ratio
0
1
2
3
4
5
6
7
8
9
10
11
12
10
20
30
40
50
60
70
80
90

increase in pressure when the mixture was stirred during explosion was due to the more intimate mixture of the gas and air molecules, rather than to any effect of increasing the velocity of inflammation by turbulence alone.

Comparison of Series 1, 2, 4, and 6.

A comparison of these series (Fig. 35) shows the higher explosion pressure produced with the cylindrical head. This is due to the smaller surface exposed in the cylindrical head as compared with the surface exposed in the L-head. Fig. 35 also shows that ignition in the center of the main chamber of the L-head vessel gives the highest maximum pressure of any of the different ignition schemes employed with the L-head. The curves for ignition at the center and in the valve chamber simultaneously and in the valve chamber alone show conclusively the influence of the narrow valve chamber in cooling the flame immediately after ignition. The time curves also corroborate the above conclusions.

Series 8 and 9.

Series 8 and 9 (Figs. 36 and 37) were run on the cylindrical head, as in Series 1. Series 8 and 9, however, were run in 1921, and on account of the difference in the characteristics of the gas used, the results differ from the results obtained in 1915, using the same vessel. As no accurate analysis of the gas used in 1915 is available, no actual comparison of the qualities of the gases can be made. Series 8 and 9, run respectively without stirring and with

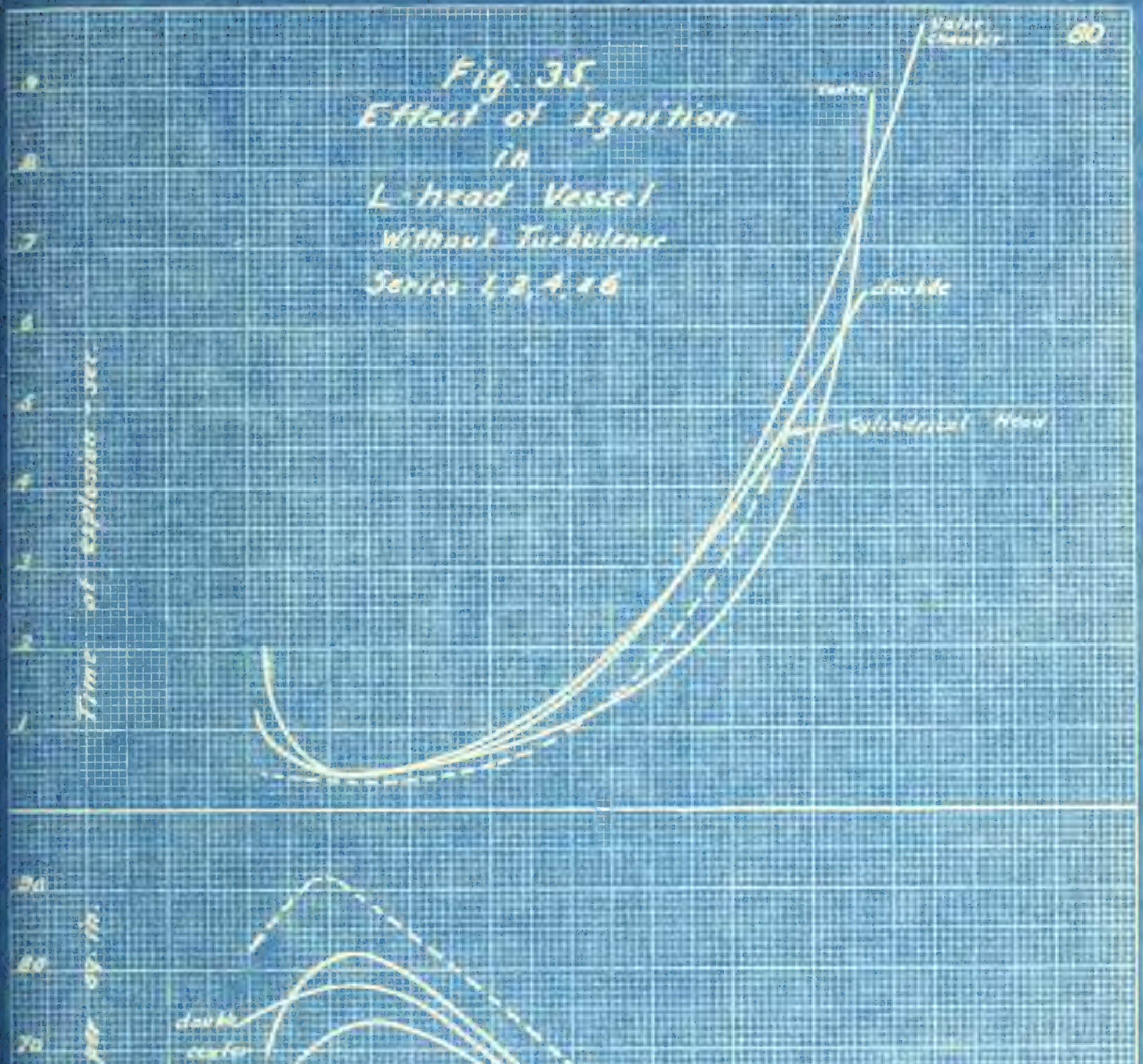


Fig. 35.
Effect of Ignition
in
L-head Vessel
Without Turbulence
Series 1, 2, 4 & 6
Valve Chamber
Center
double
Cylindrical Head
Time of explosion - sec
Maximum Pressure - lb per sq in
double
center
Valve Chamber
Cylindrical Head
Air-Gas Ratio

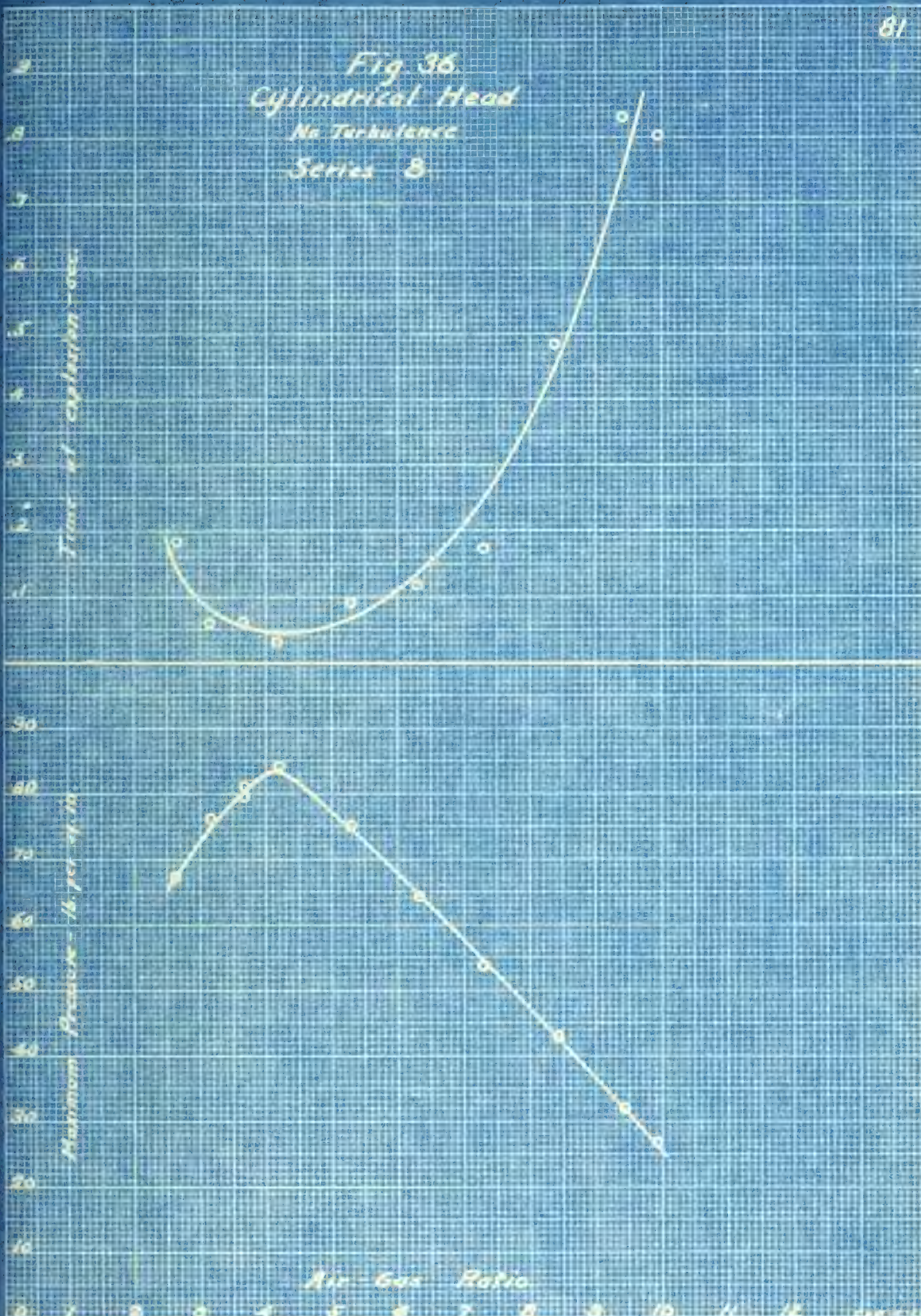


Fig. 36.
Cylindrical Head
No Turbulence
Series 8.

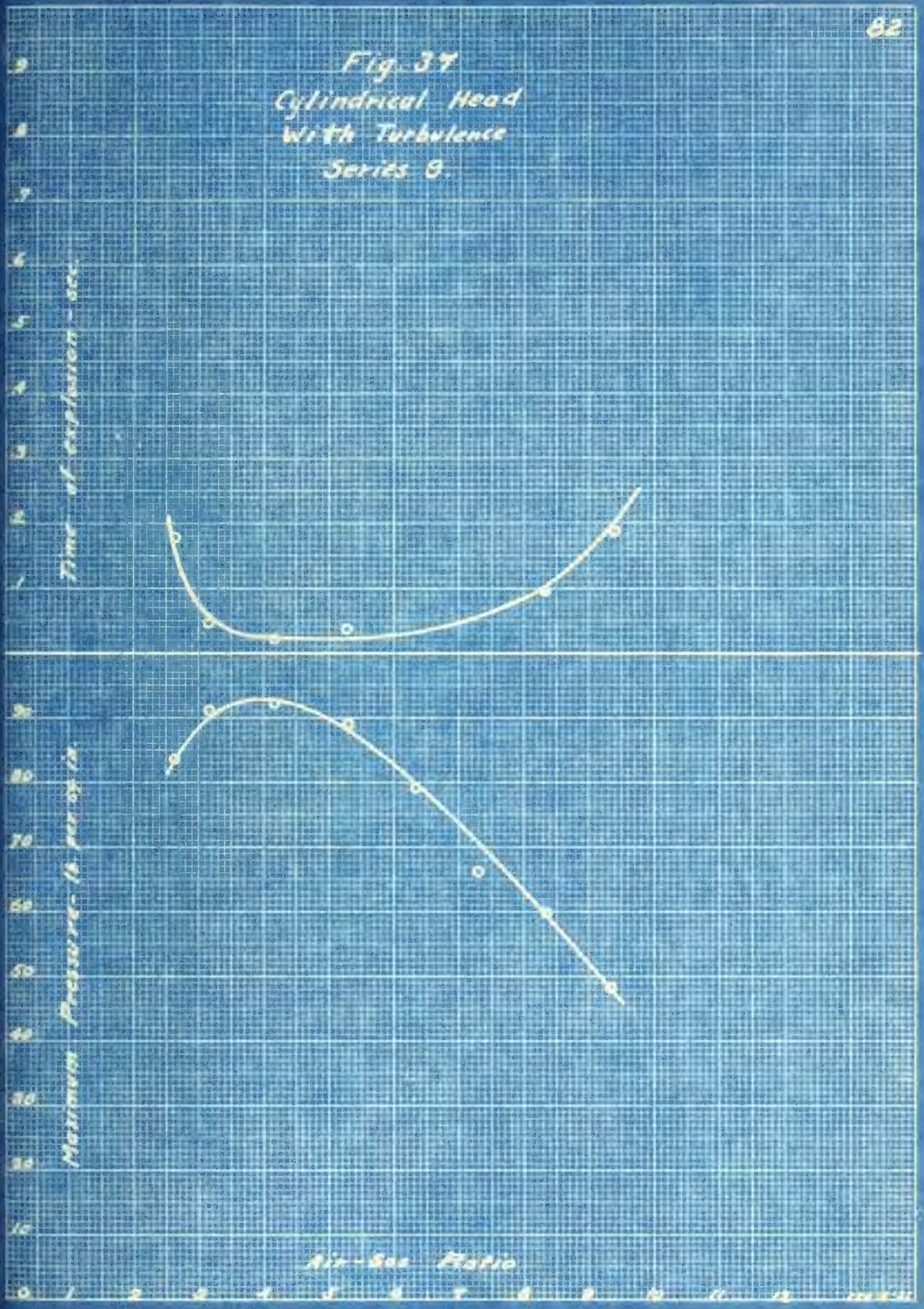


Fig. 37
Cylindrical Head
With Turbulence
Series 8.
Time of explosion - sec.
Maximum Pressure - lb per sq in
Air-Gas Ratio

stirring during explosion, are compared in Fig. 38. The increase of maximum pressure with the fan running is very marked.

Series 10 and 11.

These series (Figs. 39 and 40) were made in the conical head, with ignition occurring at the vertex of the cone. Series 10 was run with the fan in operation during the admission of the gas, and Series 11 with the fan running during both admission and explosion.

The usual increase of maximum pressure when the mixture was stirred during explosion is found by a comparison of Series 10 and 11. (Fig. 41).

Series 12 and 13.

These series (Figs. 42 and 43) were made in the conical head, with ignition three inches down from the vertex of the cone, and on the axis. Series 12 was run without stirring of the mixture, and Series 13 with stirring. Ignition was accomplished by a spark plug having long points, with the same gap length as used in the plug usually employed.

An increase of maximum pressure is found when the mixture was stirred during explosion (Fig. 44).

Comparison of Series 9, 10, 11, and 12.

A comparison of Series 9, 10, 11, and 12 (Fig. 45) leads to several conclusions relating to the decrease of maximum pressure caused by heat loss.

When ignition occurs at the vertex of the cone, a higher maximum pressure was found in all cases than when

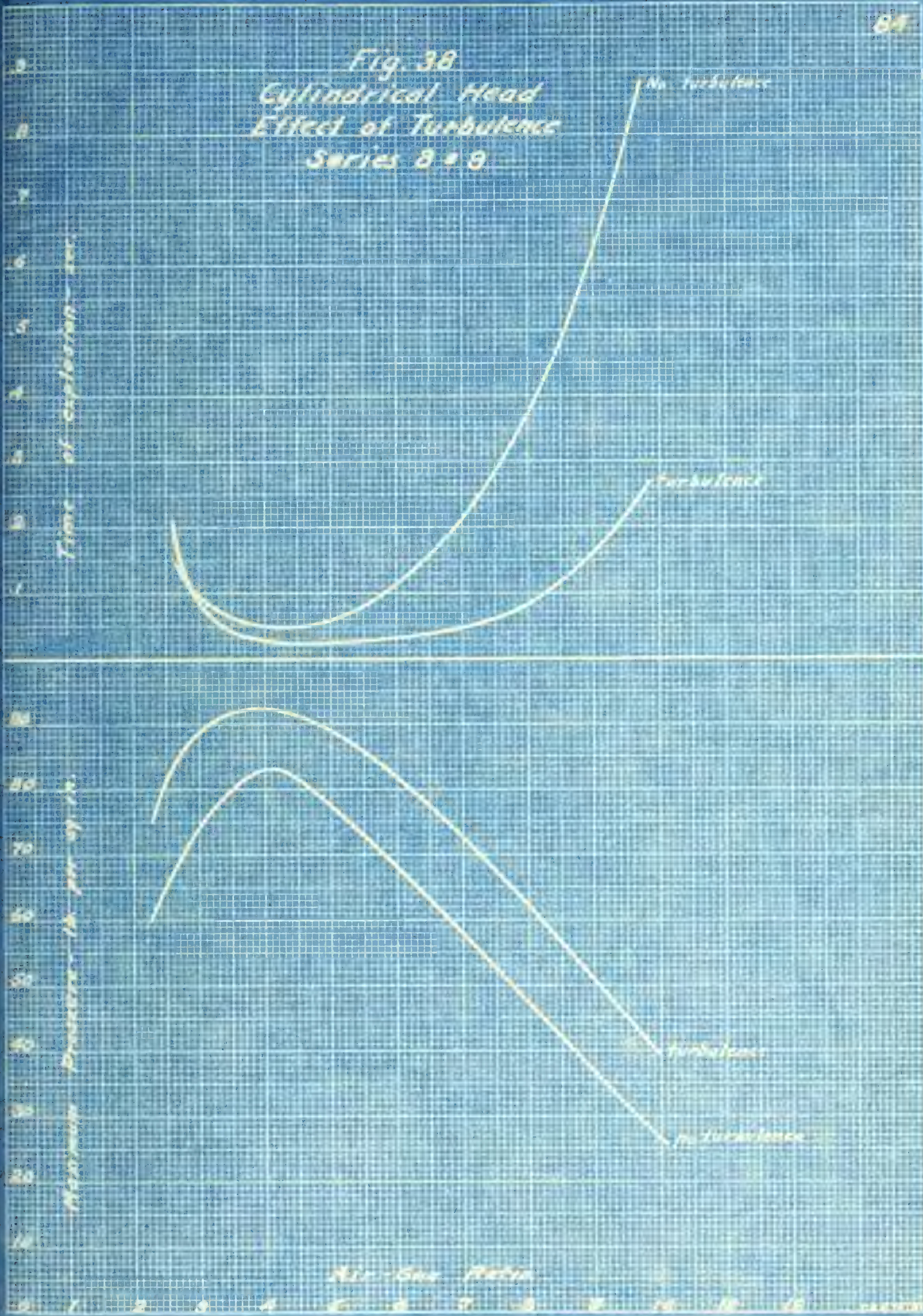


Fig. 38
Cylindrical Head
Effect of Turbulence
Series 8 & 9
No Turbulence
Turbulence
Time of explosion - sec.
Maximum Pressure - lb. per sq. in.
Turbulence
No Turbulence
Air-Gas Ratio

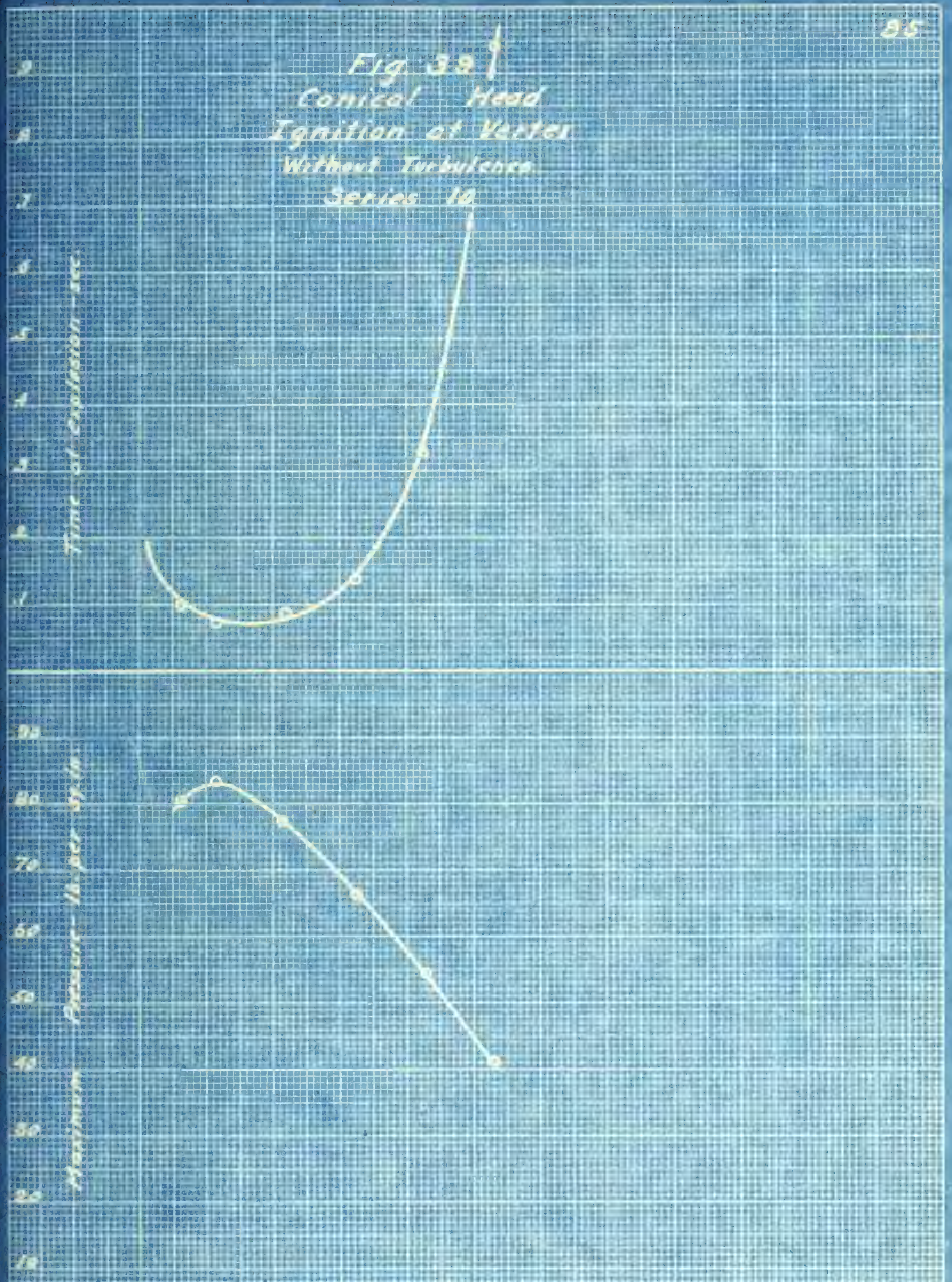


Fig. 39
Conical Head
Ignition at Vertex
Without Turbulence
Series 10
Time of Explosion - sec
Maximum Pressure - lb per sq in
Air-Gas Ratio

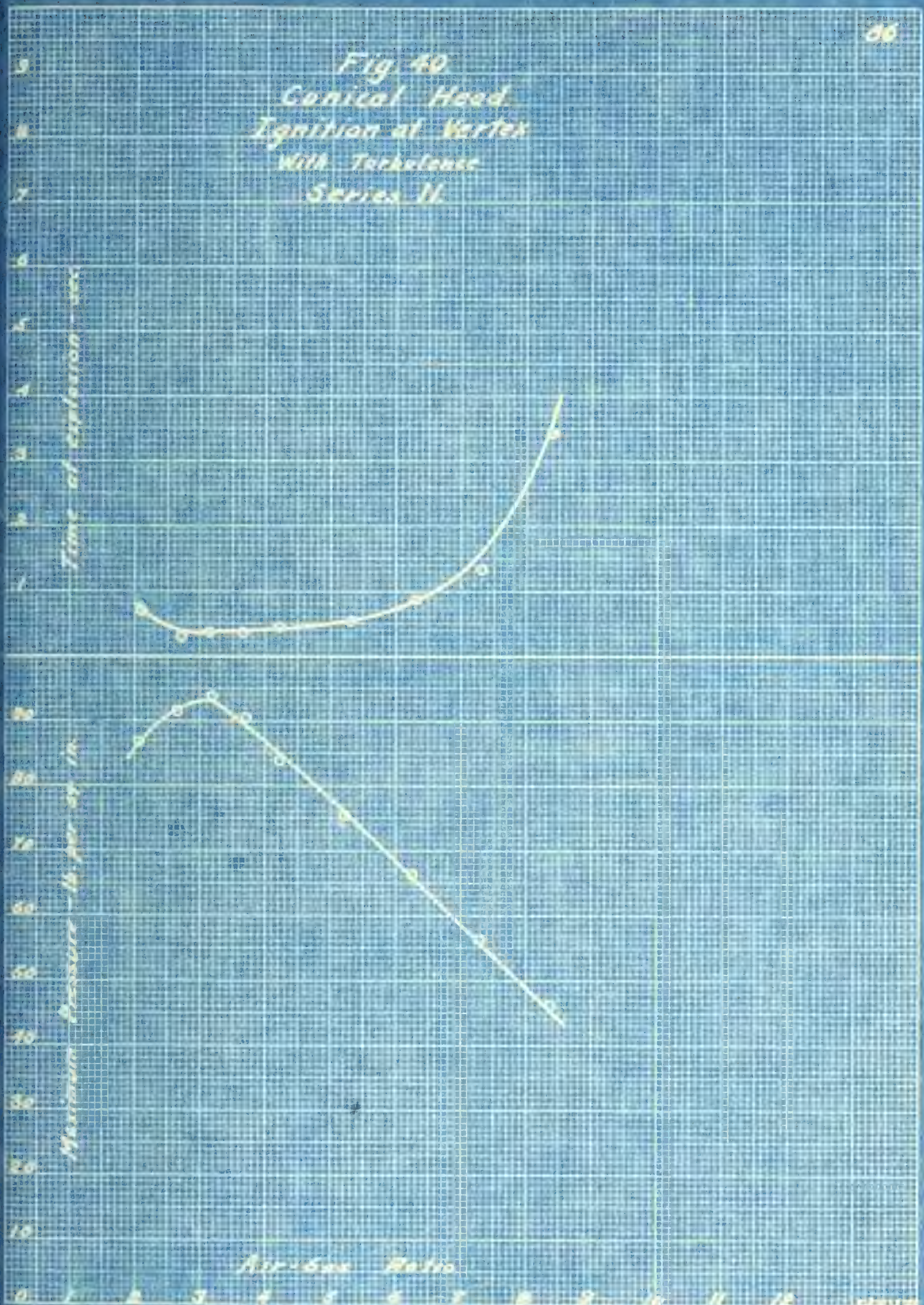


Fig. 40
Conical Head
Ignition at Vertex
Series II.
Time of explosion – sec.
Maximum Pressure – lb. per sq. in.
Air-Gas Ratio
0 1 2 3 4 5 6 7 8 9 10 11 12

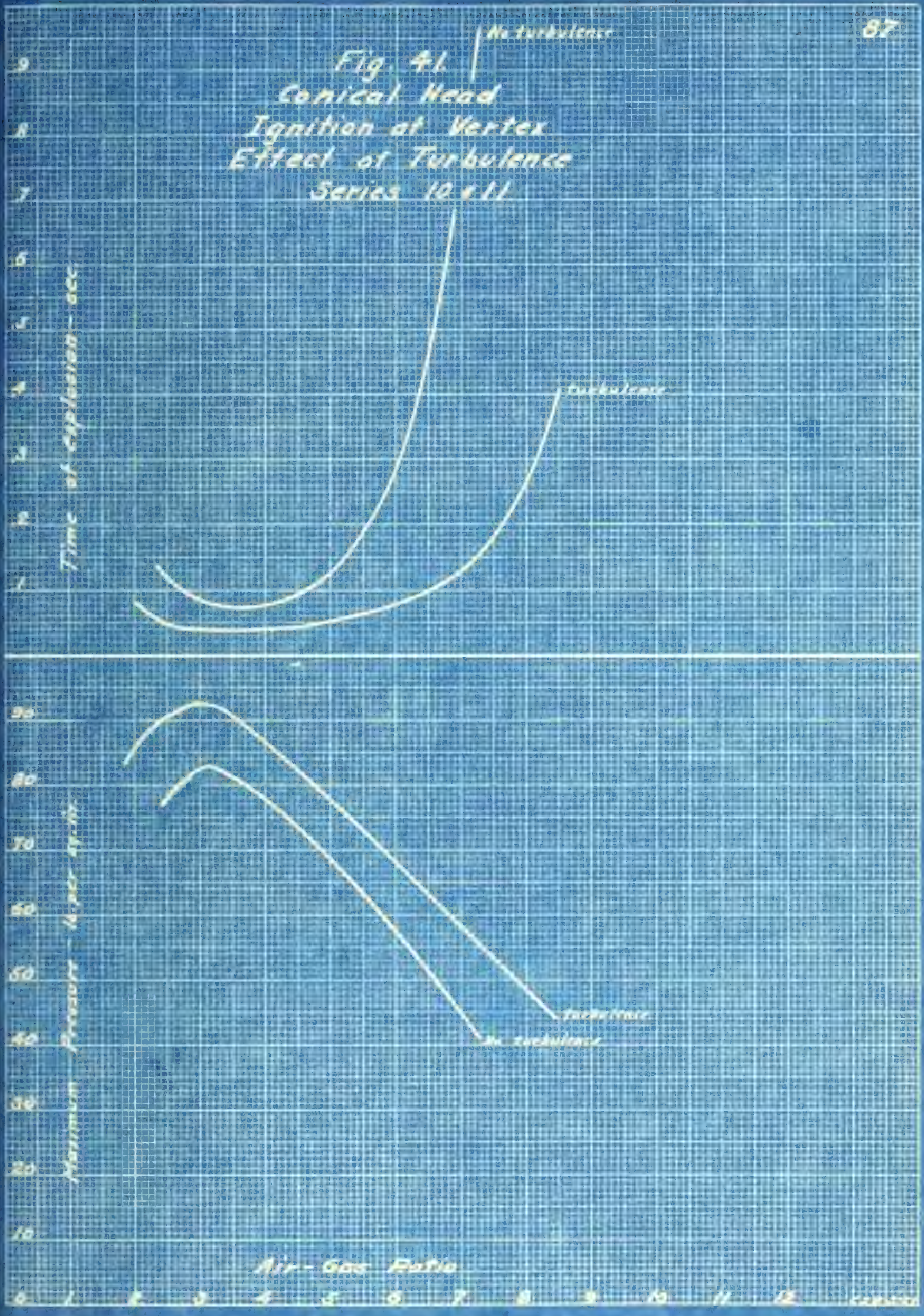


Fig. 41.
Conical Head
Ignition at Vertex
Effect of Turbulence
Series 10 & 11
No turbulence
Turbulence
Time of explosion - sec
Turbulence
No turbulence
Air-Gas Ratio

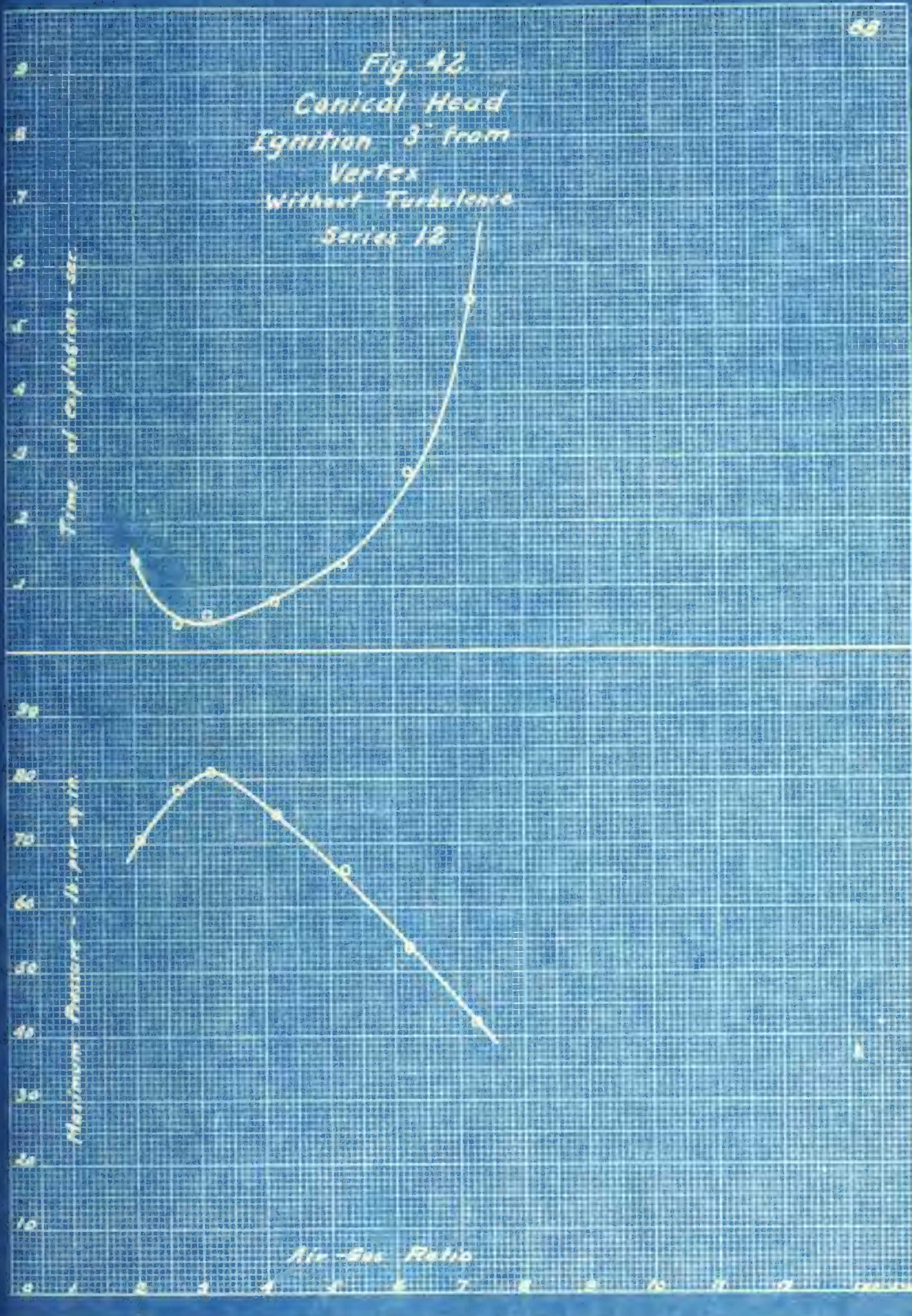


Fig. 42.
Conical Head
Ignition 3" from
Vertex
without Turbulence
Series 12
Time of Explosion - Sec.
Maximum Pressure - lb. per sq. in.
Air-Gas Ratio

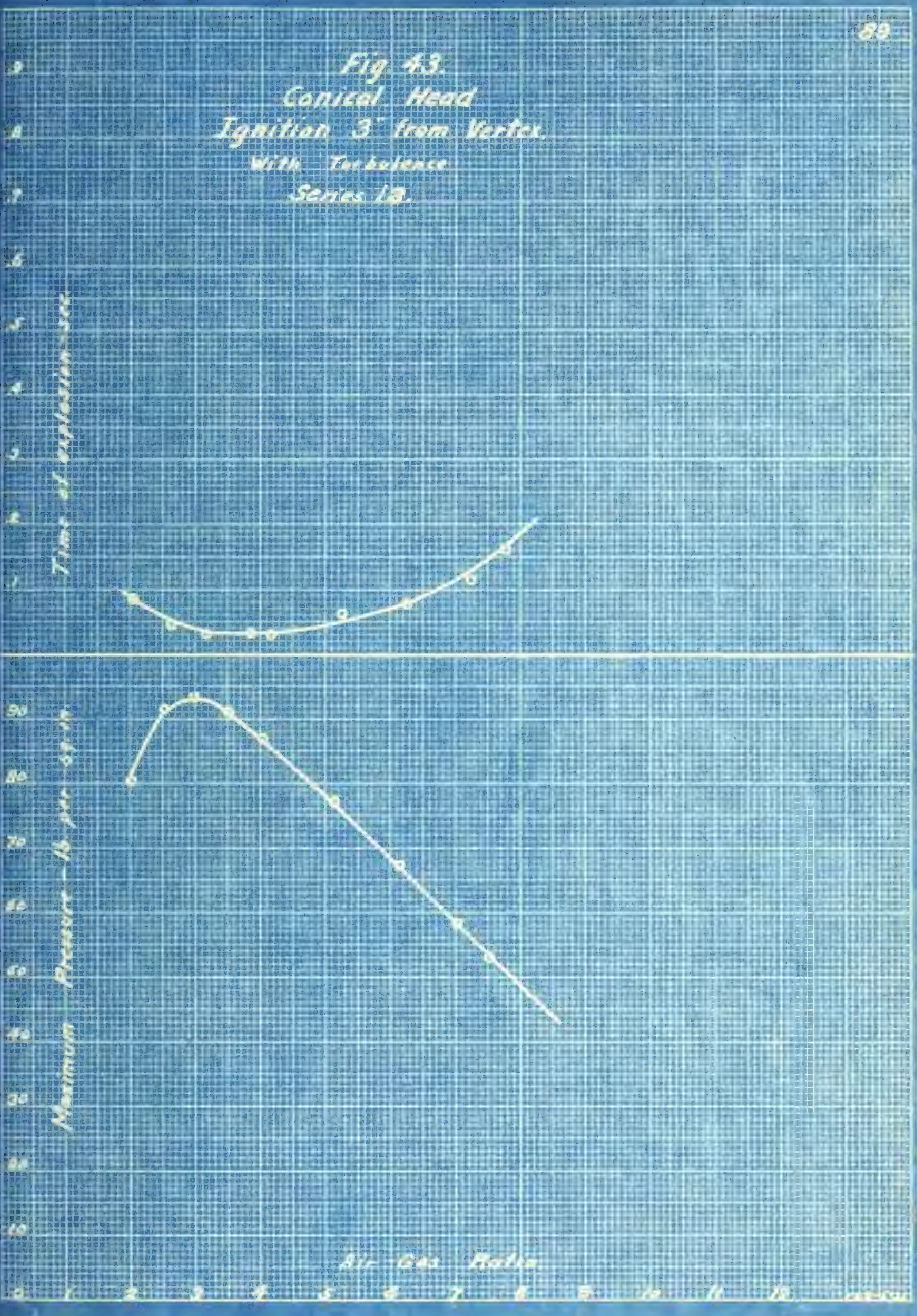
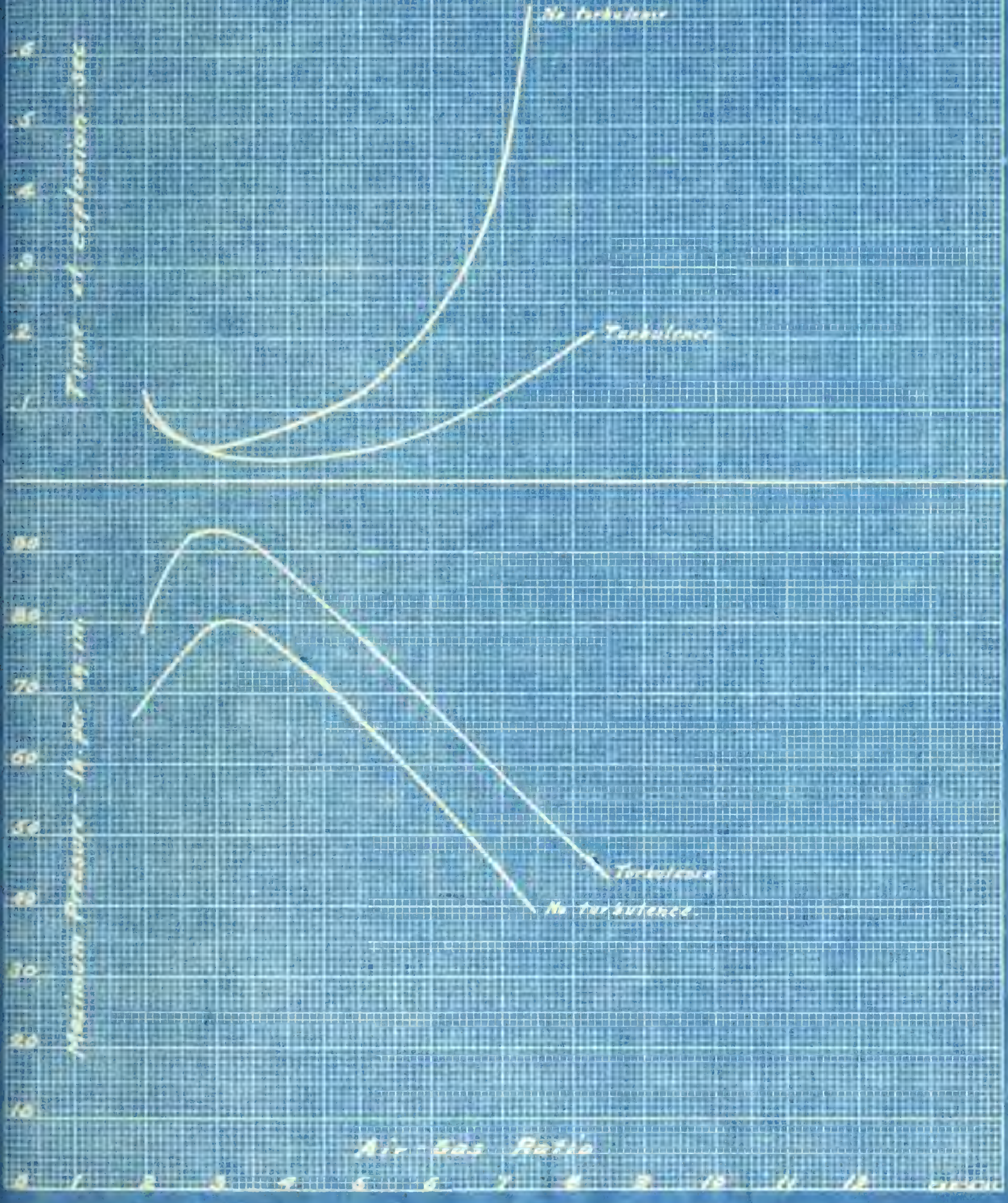


Fig 43.
Conical Head
Ignition 3" from Vertex.
With Turbulence
Series 13.
Time of explosion - sec
Maximum Pressure - lb per sq in
Air Gas Ratio

Fig. 44.
Conical Head
Ignition 3" from Vertex
Effect of Turbulence
Series 12 + 13



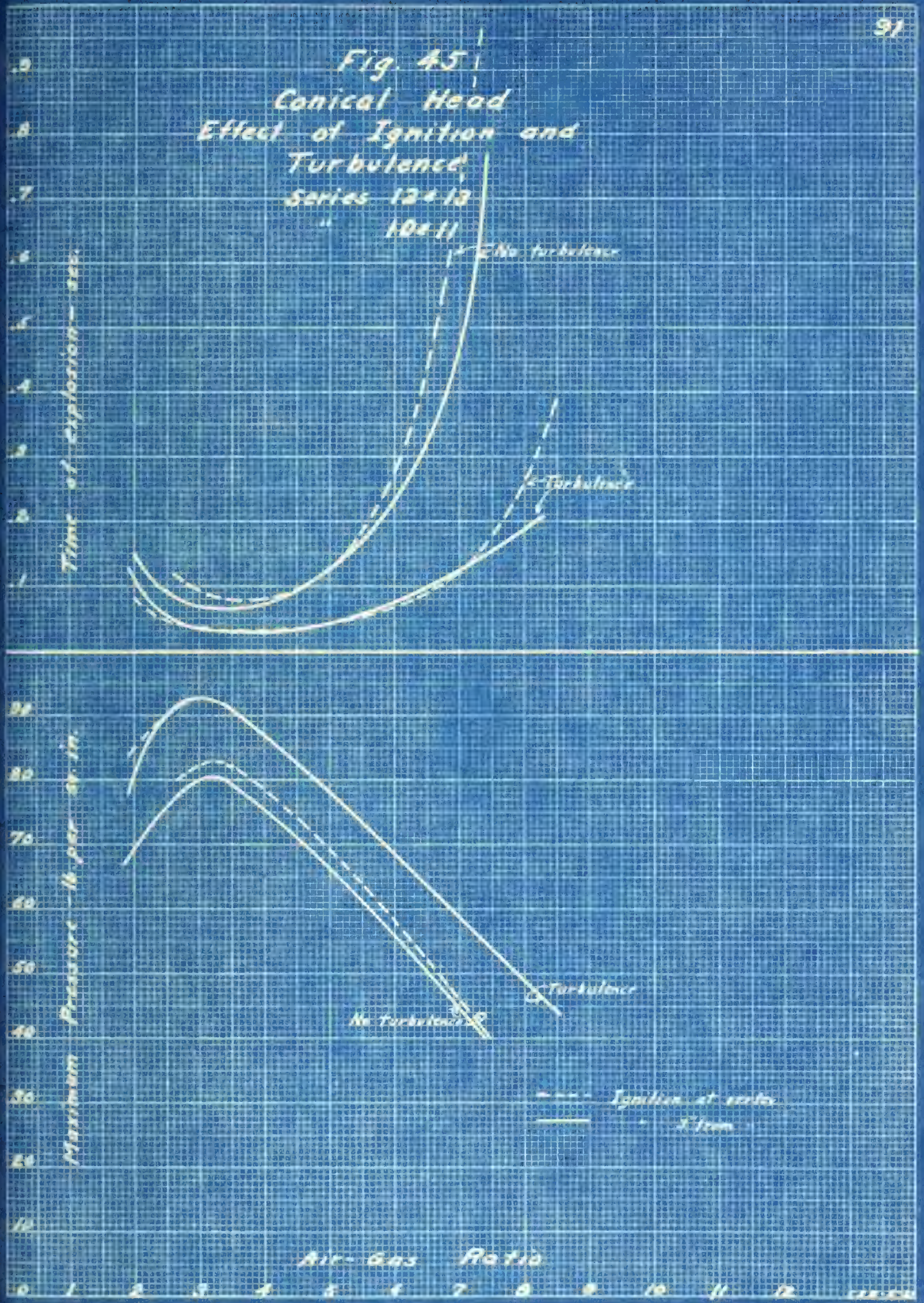


Fig. 45
Conical Head
Effect of Ignition and
Turbulence
Series 12 + 13
" 10 + 11
No turbulence
Turbulence
Time of explosion — sec.
.9
.8
.7
.6
.5
.4
.3
.2
.1
Turbulence
No Turbulence
Maximum Pressure lb per sq. in.
90
80
70
60
50
40
30
20
10
Ignition at center
" 3 from
Air-Gas Ratio
0
1
2
3
4
5
6
7
8
9
10
11
12

ignition occurred three inches down from the vertex. This difference occurred only when the mixture was not being stirred during explosion. When the fan was in operation during the explosion, the two pressure curves coincided. It is probable that a pressure wave was started when ignition occurred at the vertex, and that it advanced smoothly down the cone, expanding as though through a nozzle. This pressure wave causes higher explosion pressures to exist that if ignition occurred three inches down from the vertex, in which case the pressure wave would not be as easily set up, owing to the lack of symmetry of the vessel about the ignition point. The operation of the fan during explosion breaks up any pressure wave, and hence the same explosion pressures were obtained for the two different ignition positions when the fan was running during explosion.

It is evident from the time curves that the time of explosion differs considerably for the two positions of ignition, especially in the series in which the fan was run during explosion. The maximum pressures, however, are the same. This would indicate that the heat loss up to the time of maximum pressure is approximately the same in the two series, even though the times of explosion are quite different. It is possible, of course, that some pressure wave effect was set up even with the fan running. This would tend to counteract the increased heat loss occasioned by the longer time of explosion.

Series 14.

This series was run in the hemispherical head, with ignition occurring at the top of the vessel. No stirring of the mixture was employed during explosion. The results are plotted in Fig. 46.

Comparison of the Four Heads. (without turbulence).

In order to compare the L-head series (run in 1915) with the other series (run in 1921), Series 8 on the cylindrical head, was taken as the basis. The difference of the pressures between Series 1 and 2 was taken for various air-gas ratios, and laid off from the curve of Series 8 (which was run under the same conditions as Series 1). This gave an approximate "equivalent curve" representing the pressures developed if the 1921 gas had been used in the L-head vessel.

The curves showing maximum pressure for the four heads, using various air-gas ratios, are given in Fig. 47. The series thus compared were all run without any stirring of the mixture during explosion.

The marked advantage of the hemispherical head in producing high maximum pressures is evident from the curves.

The maximum explosion pressures produced in the four heads may be compared with the ratio of superficial area to the volume of the respective vessels.

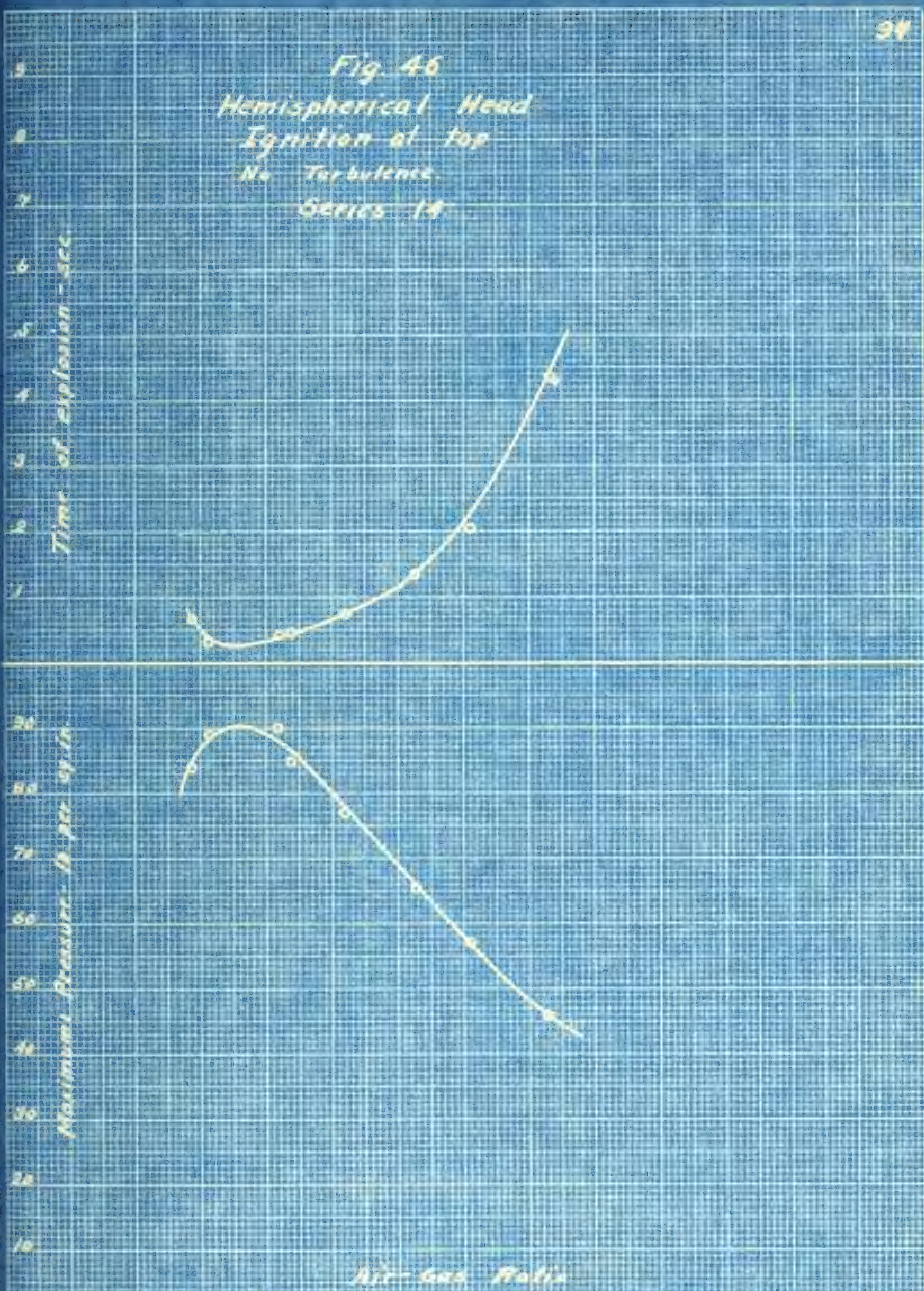
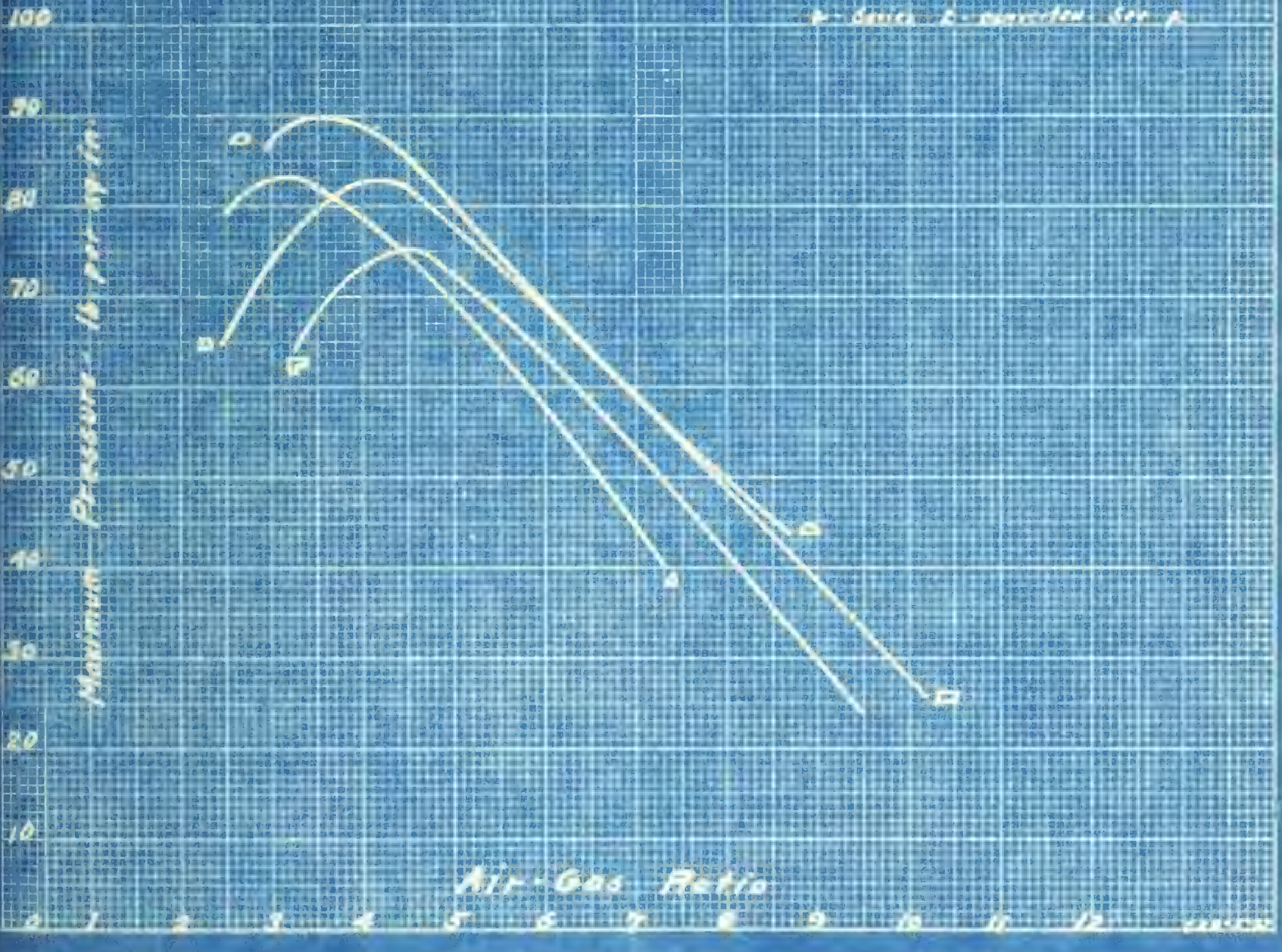


Fig. 46
Hemispherical Head
Ignition at top
No Turbulence
Series 14
Time of explosion - sec
Maximum Pressure lb per sq in
Air-Gas Ratio

Fig. 47
Comparison
of
Four Heads
Series 2*, 8, 10, & 14



	Ratio A/V	Max. Pressure
Hemispherical head	0.69	90.0
Cylindrical "	1.24	84.0
Conical "	1.34	83.0
L- "	1.62	75.0

These results are plotted in Fig. 48. The cooling influence of the different wall areas is very noticeable from this curve.

Cooling after Explosion.

After the attainment of the maximum pressure the mixture cools at a rate depending on

1) the air-gas ratio.
2) the character of the walls of the vessel.
3) the ratio of surface to volume of the vessel.

In Fig. 49 the cooling curves for mixtures of approximately 3 parts of air to 1 of gas are shown. These curves were constructed directly from the cooling curves on the indicator diagrams taken on the various heads. The initial temperature in each case was taken as 2912 deg. F. Allowance was made in these calculations for the reduction in volume of the gases after combustion.

In Fig. 50 are plotted curves of temperature drop in 0.2 sec. and 0.5 sec. (from the initial temperature 2912 deg. F.) against the ratio of surface to volume for each of the four vessels used in this investigation. It will be noted that three points fall on a straight line. One point

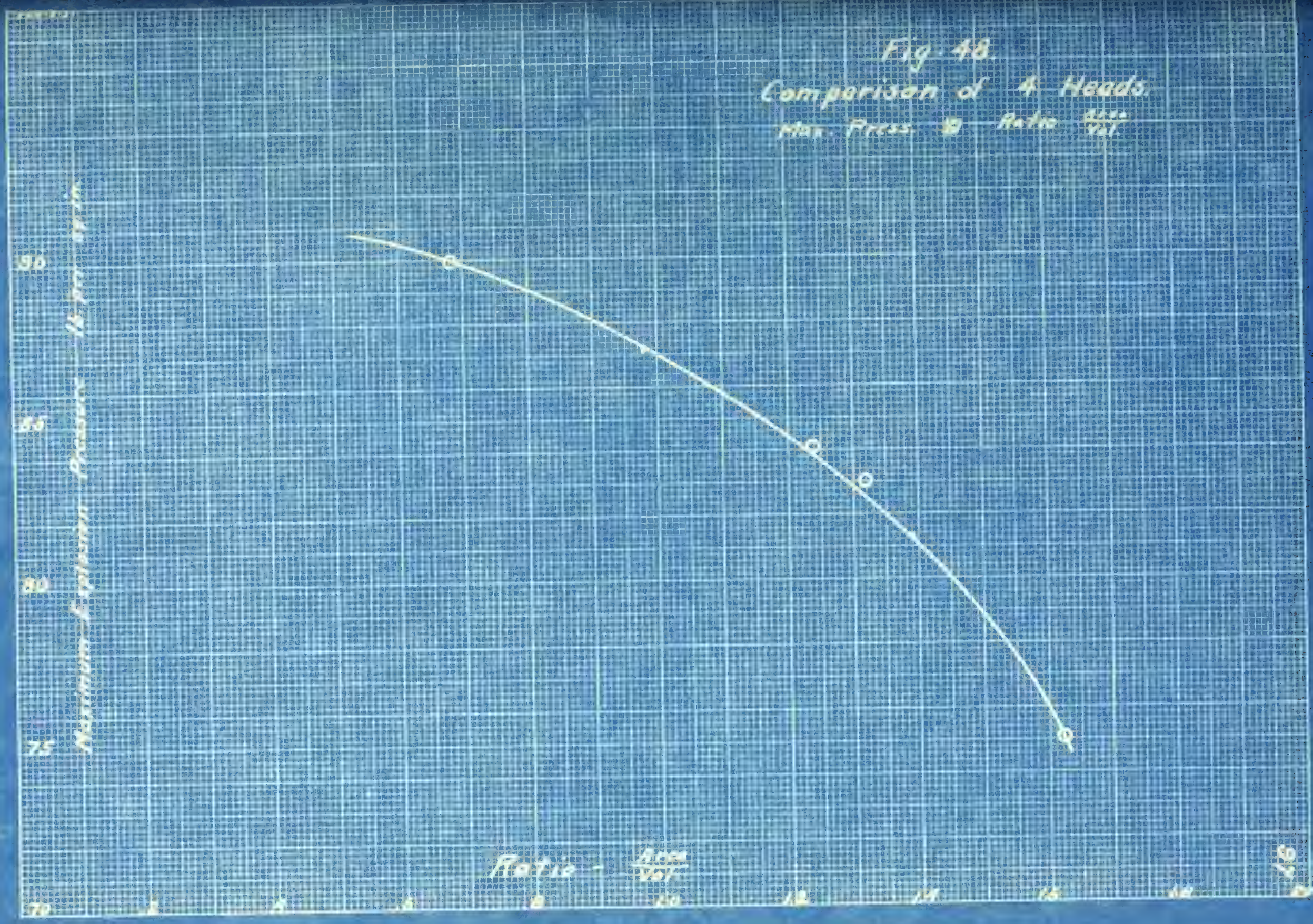
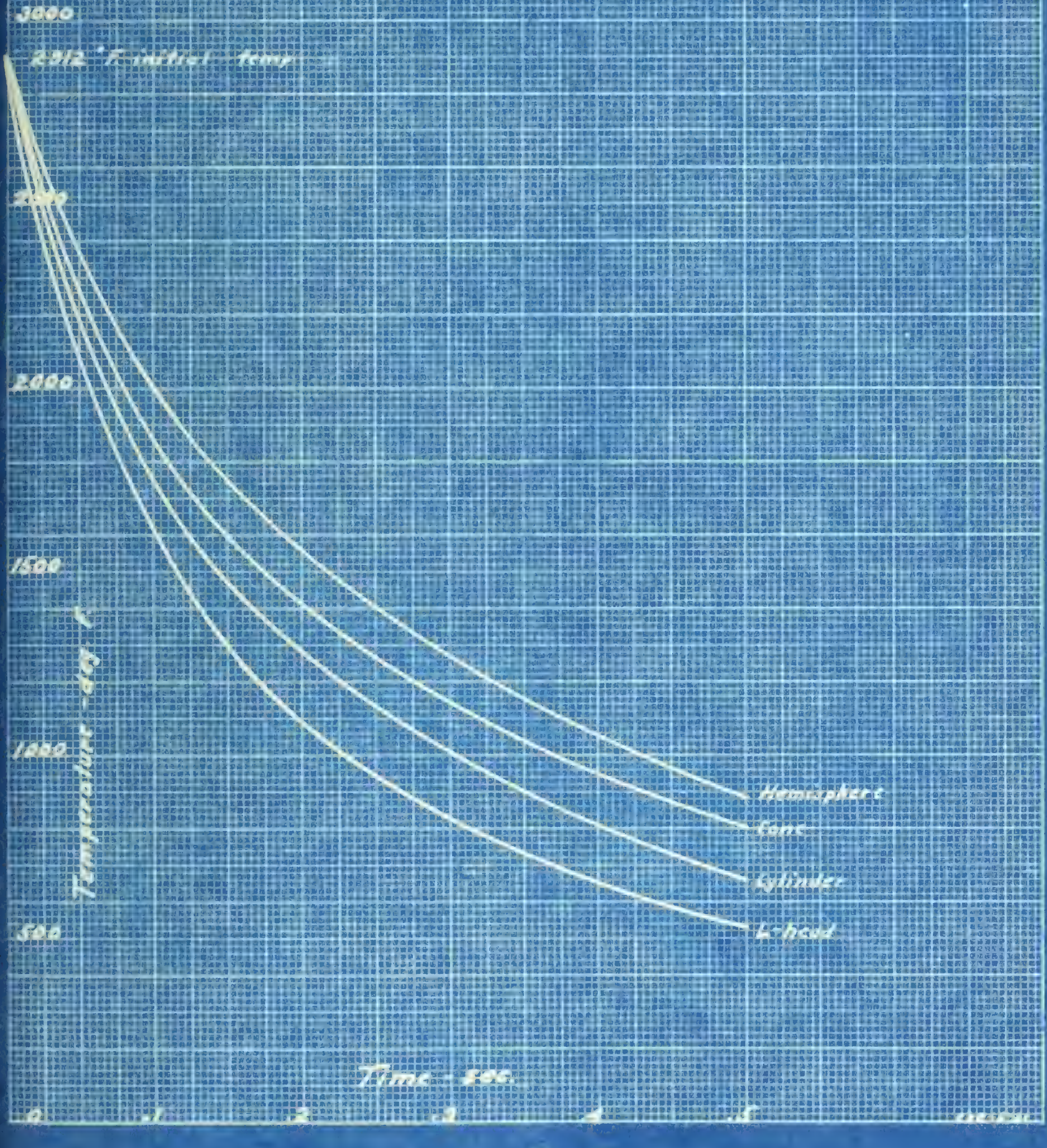


Fig. 48.
Comparison of 4 Heads.
Max. Press. to Ratio $\frac{Area}{Vol.}$
Maximum Explosion Pressure - lb. per sq. in.
90
85
80
75
70
Ratio - $\frac{Area}{Vol.}$
2
4
6
8
10
12
14
16
18
20

Fig. 43
Cooling Curves



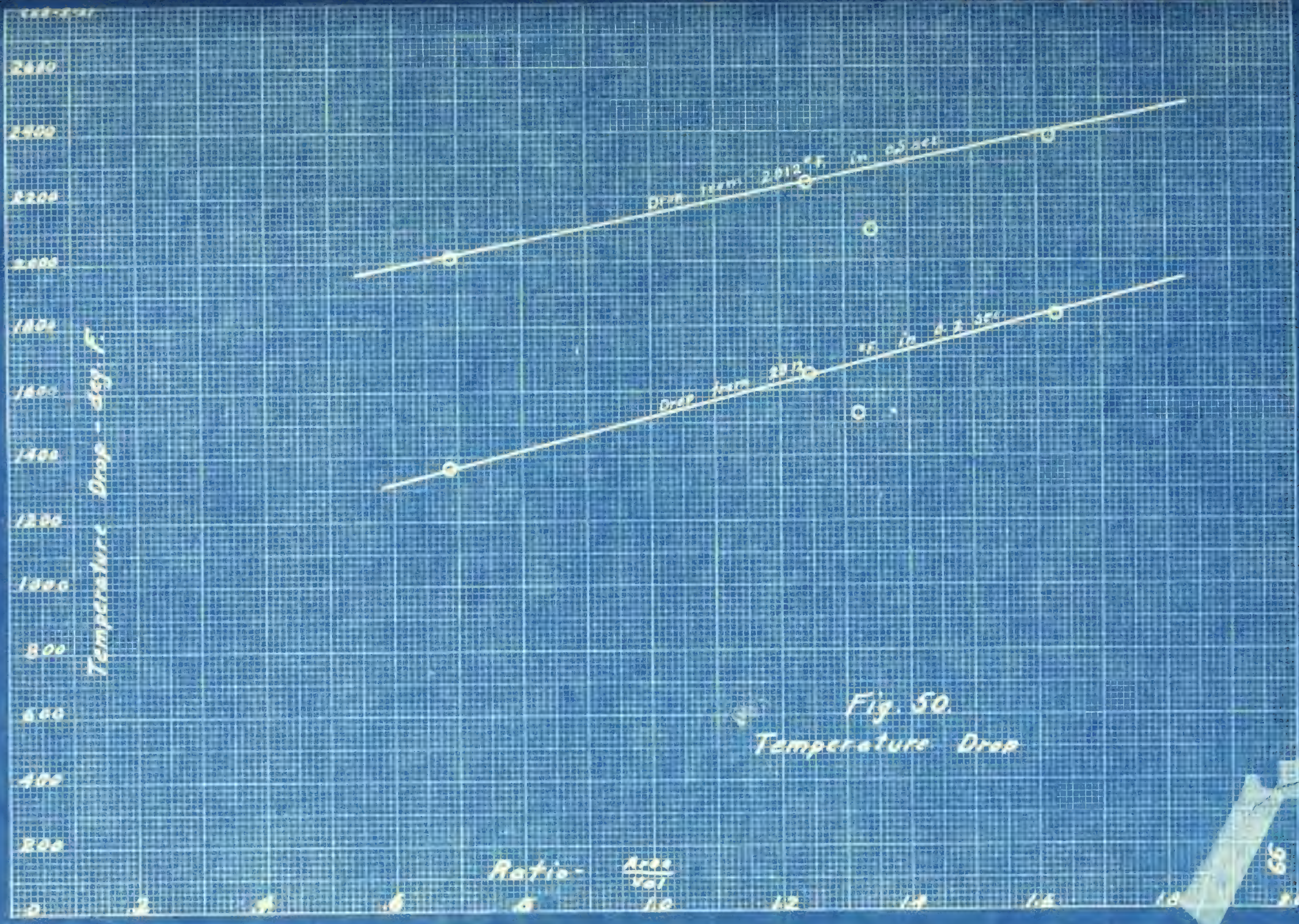


Fig. 50
Temperature Drop

(derived from the cooling of mixtures in the conical head) shows a smaller drop in temperature than would be expected from the values taken from the other vessels. The inner surface of the concial head was much cleaner and more polished than the other heads used, which were rusted and blackened considerably. It is probable therefore that the conical head reflected a considerable amount of the radiant heat falling on the walls, and hence the mixtures cooled more slowly in this head than in the others. The agreement of the three points on the straight line seems to substantiate the linear relation of temperature drop in a given time to the ratio of surface to volume.

Hydrogen-Air Explosions

Mixtures of hydrogen and air were exploded in the conical vessel under a number of different conditions of ignition and turbulence, in order to study the heat loss during the time of explosion. Three mixtures were used, namely:-

1) $H_2 + \frac{1}{2}O_2 + 1.9N_2$

2) $H_2 + O_2 + 3.8N_2$

3) $H_2 + 1\frac{1}{2}O_2 + 5.7N_2$

For some of the explosions a special "six-gap" spark plug was used, which had six gaps of about 0.03" each, spaced about one inch apart. This plug, when in place, gave a series of sparks along the axis of the cone, at intervals from the vertex to the base. Very rapid ignition was accomplished by the use of this plug in conjunction with the fan.

Each of the above mixtures was exploded under the following conditions:-

Ignition at vertex	Fan not running.
" " "	" running.
" 3 in. down	" not running.
" " "	" running.
" with 6-gap plug	" not running.
" " " "	" running.

Some further minor variations were made in the ignition conditions in special cases.

A table of the above described results follows on the next page.

Results of Hydrogen-Air Explosions.

Test No.	Max. Press. Lb. per sq. in.	Time of explosion seconds.
$H_2 + \frac{1}{2}O_2 + 1.9N_2$		
H1	75.0	0.0175
H2	78.0	0.0146
H4	86.0	0.0098
H5	77.0	0.0161
H25	82.5	0.0126
H26	84.8	0.0095
H27	79.2	0.0148
$H_2 + O_2 + 3.8N_2$		
H11	65.0	0.0077
H19	50.8	0.0251
H20	58.3	0.0148
H21	59.5	0.0105
$H_2 + 1\frac{1}{2}O_2 + 5.7N_2$		
H6	45.3	0.0970
H7	45.3	0.0920
H8	47.3	0.0227
H9	45.3	0.0544
H10	46.3	0.0527

The experiments just described furnish data on the maximum pressures developed and the times of explosion of mixtures of hydrogen and air, with the mixture in any one of the three series held constant, and ignition and turbulence conditions varied to obtain various times of explosion and corresponding maximum pressures.

If the maximum pressure is plotted against the time, curves as in Figs. 51, 52, and 53 are obtained. If the line through the series of points in any one of these curves is prolonged to intersect with the axis of pressure, (or zero time) the point of intersection will give the theoretical maximum pressure which would be developed if no heat loss to the walls of the vessel occurred.

Hopkins states that the heat loss varies with the square root of the time from ignition. This statement appears to be confirmed from the shape of the curves in Figs. 51, 52, and 53. The curve in Fig. 51 is practically a straight line, as the mixture exploded very rapidly. This line corresponds to the first part of the "square root curve" cited by Hopkinson.

The maximum pressures, assuming no heat loss during explosion, have been calculated (Appendix I) as follows:-

Mixture with $\frac{1}{2}O_2$	101.1 lb. per sq. in. gage.
" " O_2	75.4 " " " " "
" " $1\frac{1}{2}O_2$	55.4 " " " " "

The curve through the observed points checks the calculated

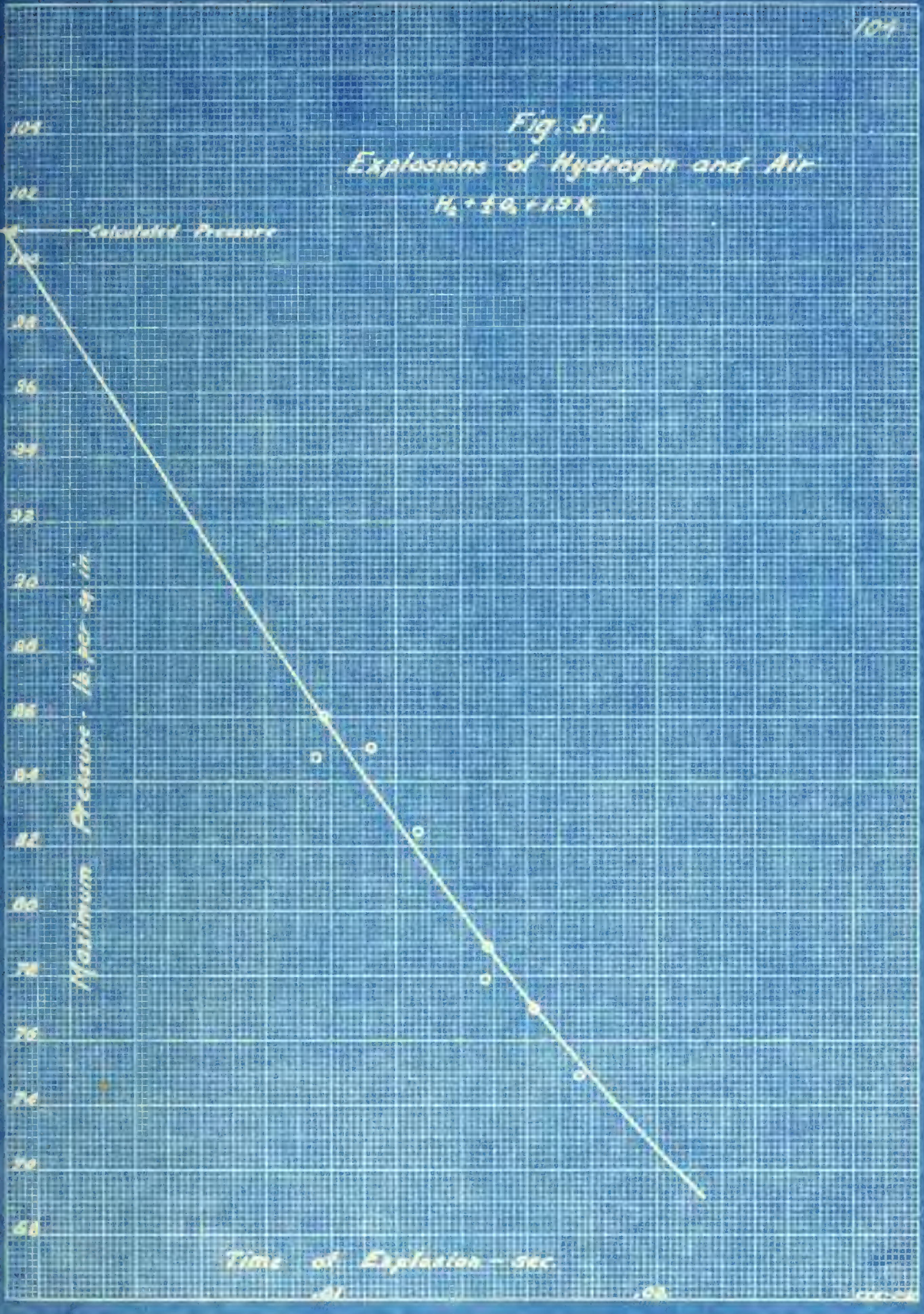


Fig. 51.
Explosions of Hydrogen and Air
$H_2 + \frac{1}{2}O_2 + 1.9N_2$
Calculated Pressure
Maximum Pressure - lb. per sq. in.
104
102
100
98
96
94
92
90
88
86
84
82
80
78
76
74
72
68
Time of Explosion - sec.
.01
.02

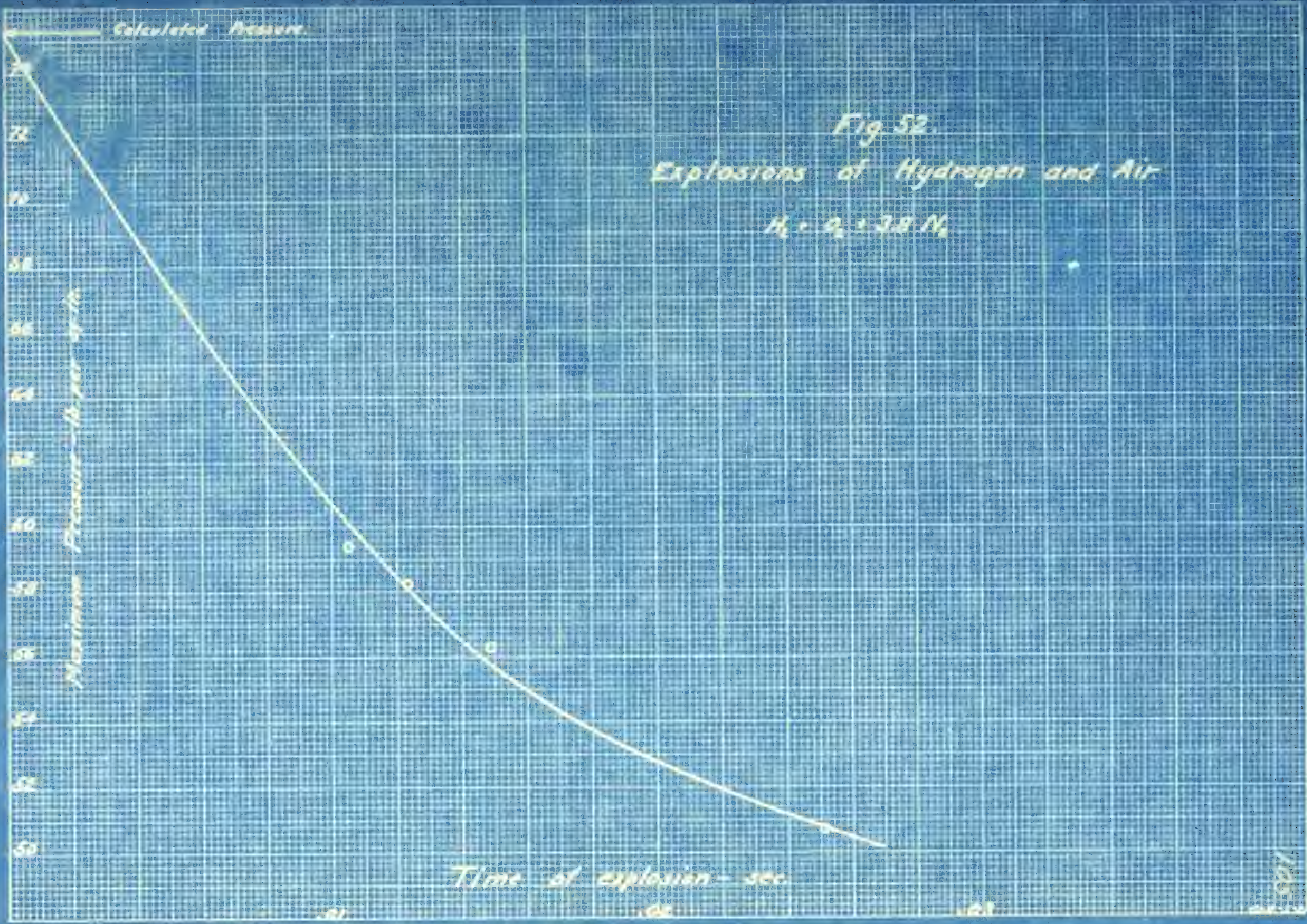


Fig. 52.
Explosions of Hydrogen and Air
$H_2 + O_2 + 3.8 N_2$

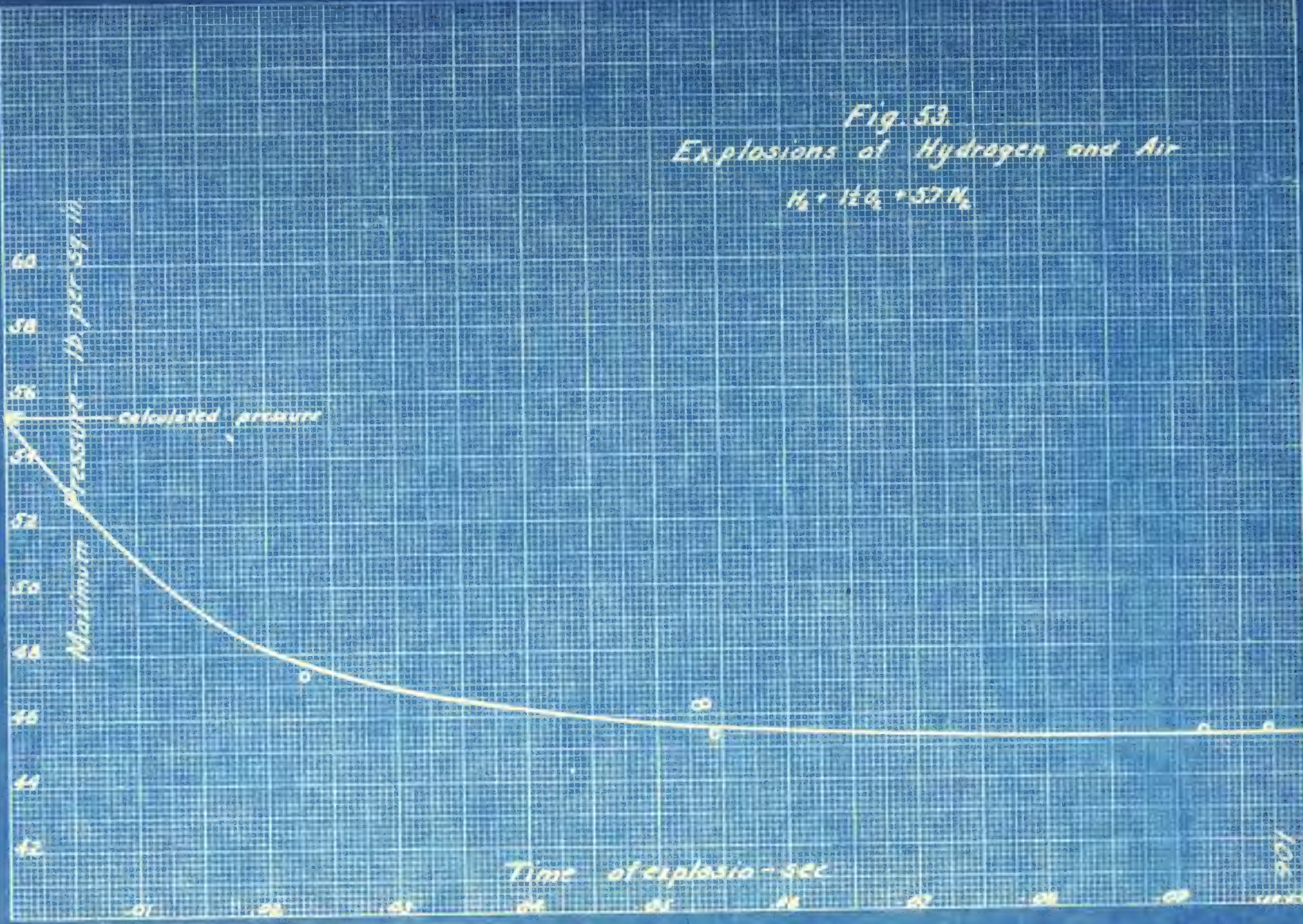


Fig. 53.
Explosions of Hydrogen and Air
$H_2 + \frac{1}{2}O_2 + 5.7 N_2$

point closely in each case.

The minimum loss of pressure due to cooling during explosion is as follows:-

Mixture with $\frac{1}{2}O_2$	12.9% loss.
" " O_2	21.2 "
" " $1\frac{1}{2}O_2$	14.6 "

Such large losses are not usually found, but these are due to the small volume of the vessel used and the rapid cooling, as shown in Fig. 49, as compared with the vessels used by other experimenters.

It is probable that much further data on the heat loss during explosion could be obtained by a study of explosions such as these just discussed. By making the walls of the vessel totally absorbing or partially reflecting the radiation losses might be separated out and a study made of the conduction and radiation losses separately.

VI. CONCLUSIONS

From the results of this investigation the following conclusions may be drawn.

1) The conclusions of other experimenters as to the influence of the air-gas ratio on the maximum pressure and the time of explosion have been confirmed.

2) In general, the effect of turbulence of the mixture during explosion is to bring about an increase of maximum pressure and a decrease of the time of explosion.

3) The effect of turbulence is largely that of producing a more intimate mixture of the gas and air molecules before combustion, rather than that of projecting the flame into the unburned parts of the gas mixture.

4) The position of the spark gap (in vessels patterned after the combustion spaces in use in gas engines) has a considerable influence on the rate of inflammation and on the maximum pressure.

5) There is evidence in certain cases of the formation of pressure waves (of different character than trues explosions waves) which travel smoothly through the vessel and produce higher maximum pressures than if inflammation proceeded in the ordinary way.

6) The maximum pressure and time of explosion are mater-

ially affected by the shape of the explosion vessel, the primary cause of this effect being the variation in the ratio of surface to volume for the different vessels.

7) The combustion of the gases in any pocket in the vessel (such as the valve chamber in the L-head vessel) is often incomplete, due to the cooling effect of the walls, which reduces the maximum pressure.

8) The cooling of the mixture in any given time after explosion and maximum pressure varies directly with the ratio of surface to volume for the explosion vessel, other conditions being constant.

9) Radiation evidently plays an important part in the cooling of the mixture, as a change in the character of the inner surface of the walls of the vessel causes a considerable change in the cooling curve.

10) Hopkinson's statement that the heat loss to the walls of the vessel varies as the square root of the time from ignition has been confirmed for the loss during the explosion period.

11) A method of evaluating the loss of heat during explosion has been demonstrated.

12) Calculations of the maximum pressure, based on the properties of the gas mixture, have been checked by experimental results for the explosions of hydrogen and air. mixtures.

TABLE OF RESULTS

OF

EXPLOSIONS OF ILLUMINATING GAS AND AIR

Series 1

Cylindrical head.
No stirring.
Ignition at top.

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
48	3.21	87.1	0.0510
49	3.77	92.5	.0438
50	4.06	92.0	.0366
51	4.99	84.1	.0450
52	6.10	73.4	.0668
53	7.03	66.2	.0999
54	8.60	52.0	.2390
55	9.43	44.5	.4010
56	11.34	7.0	.6280
57	3.62	86.5	.0544
58	4.06	88.5	.0370
59	4.59	87.5	.0363

Series 2

L-head.
No stirring.
Ignition at center.

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
62	3.91	82.0	0.----
63	4.97	76.5	0.0471
64	5.79	67.5	.0549
65	7.25	57.0	.----
66	8.41	48.0	.----
66a	8.17	49.1	.----
67	9.71	36.5	.3460
68	10.65	21.0	.7220
82	2.83	----	.----
83	3.26	71.0	.1830
84	3.64	78.8	.0578
85	4.16	82.2	.0381
86	4.87	80.5	.0433
87	5.80	68.0	.0637
88	7.17	57.0	.1218
89	8.49	47.0	.2163
90	10.57	21.0	.7450
134	5.87	68.1	.0623
135	7.52	52.5	.1455
168	8.82	40.1	.4230
169	9.99	21.1	.7600
170	8.09	48.0	.2070
171	9.03	40.1	.4180

Series 3

L-head.
Stirring during explosion.
Ignition at center.

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
118	3.03	80.5	0.1265
119	3.31	83.2	.0588
120	4.20	87.0	.0223
121	4.66	88.0	.0187
122	4.99	84.1	.0204
123	6.11	74.1	.0286
124	7.01	66.0	.0371
125	8.23	59.0	-----
126	9.40	50.8	.1057
127	10.27	48.1	.1718
128	11.87	----	-----
129	8.39	59.0	.0304
130	4.70	88.0	.0178
132	11.00	----	-----
133	3.23	80.5	.0702

Series 4

L-head.
No stirring.
Ignition in valve chamber.

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
69	3.18	61.5	0.0776
70	3.61	70.8	.0557
71	4.06	71.0	.0474
72	4.96	73.3	.0504
73	5.68	66.1	.0760
74	7.06	55.0	.1455
75	9.26	41.5	.3280
76	9.64	35.7	.5100
77	10.81	12.5	.7670
78	2.91	58.0	.3790
79	4.14	72.5	.0450
80	6.93	52.2	.1179
82	4.04	74.4	.0431
91	8.03	43.5	.2970
92	9.12	36.5	.4620
93	10.10	21.0	----
94	10.20	22.1	.8070
95	11.03	6.0	.8860

Series 5

L-head.
Stirring during explosion.
Ignition in valve chamber.

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
136	3.66	74.1	0.0455
137	3.29	78.7	[illegible]
138	4.14	84.2	.0196
139	4.76	84.2	[illegible]
140	5.05	85.2	.0209
141	6.04	74.1	.0272
142	7.35	65.3	[illegible]
143	8.32	57.0	.0528
144	9.46	51.5	.0728
145	10.44	49.1	[illegible]

Series 6

L-head.
No stirring.
Ignition in center and valve chamber

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
146	3.05	74.1	0.0538
147	[illegible]	75.1	.0502
148	4.05	76.2	.0471
149	4.75	81.5	[illegible]
150	[illegible]	[illegible]	.0501
151	[illegible]	65.5	.9705
152	[illegible]	53.5	.1690
153	8.50	41.9	.2940
154	[illegible]	[illegible]	.4495
155	10.50	17.5	.5890

Series 7

L-head.
Stirring during explosion.
Ignition at center and valve chamber.

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
156	3.08	78.7	0.0532
157	3.49	85.1	.0224
158	4.18	88.0	.0151
159	4.78	87.0	.0175
160	4.70	87.0	.0222
161	5.20	83.2	.0223
162	6.21	72.5	.0343
163	7.07	65.2	.0390
164	8.31	57.0	.0548
165	9.28	51.5	.0693
166	10.40	43.6	.1482
167	11.14	19.5	.2660

Series 8

Cylincrical head.
No stirring.
Ignition at top center.

206	4.17	84.5	0.030
209	5.29	75.5	.095
211	6.25	64.5	.11[illegible]
212	8.33	43.5	.48[illegible]
214	9.37	32.5	.852
215	11.47	----	---
216	[illegible].08	---	---
217	3.65	81.0	.---
218	7.29	54.0	.172
219	[illegible].61	67.5	.181
220	99.0	27.0	.806
221	3.65	80.[illegible]	.061
222	3.13	76.5	.058

Series 9

Cylindrical head.
Stirring during explosion.
Ignition at top center.

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
223	3.13	91.0	0.046
225	4.17	92.0	.026
226	5.29	89.0	.033
227	6.25	78.5	.044
228	7.29	66.5	---
230	9.37	49.0	.185
231	10.42	----	---
232	11.47	----	---
233	2.08	----	---
234	2.61	83.5	.171
237	8.53	60.0	.095
238	9.90	----	---

Series 10

Conical head.
No stirring.
Ignition at vertex.

274	3.13	83.6	0;071
275	2.61	80.0	.095
276	4.17	78.0	.083
277	5.21	66.5	.139
278	6.25	54.3	.329
279	7.29	40.6	.942
280	8.33	----	---

Series 11

Conical head.
Stirring during explosion.
Ignition at vertex.

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
329	2.08	87.0	0.0700
330	2.61	91.5	.0280
331	3.13	93.8	.0390
332	3.65	90.3	.0380
333	4.17	83.6	.0516
334	5.21	75.5	.0496
335	6.25	66.6	.0810
336	7.29	56.5	.1360
337	8.33	46.3	.3140

Series 12

Conical head.
No stirring.
Ignition 3" from vertex.

306	2.61	78.0	0.040
307	4.17	73.5	.079
308	5.13	81.6	.056
310	5.21	65.5	.132
311	6.25	53.5	.271
312	7.29	41.2	.550
313	8.33	----	---
314	2.08	60.0	.136
315	7.81	7.0	---

Series 13

Conical head.
Stirring during explosion.
Ignition 3" from vertex.

Test No.	Air-gas ratio	Max. Press. lb. per sq. in.	Time of expl. sec.
316	2.08	80.3	0.088
317	2.61	91.5	.044
318	3.13	93.8	.036
319	3.65	91.5	.038
320	4.17	87.0	.034
323	7.29	59.5	.119
324	7.81	52.0	.167
325	8.85	44.8	.267
326	9.37	5.0	---
327	5.21	79.0	.064
328	6.25	68.0	.088

Series 14

Hemispherical head.
No stirring.
Ignition at top.

350	3.14	89.0	0.0391
351	4.20	90.5	.0465
352	5.18	77.5	.0732
353	6.25	66.2	.1330
354	7.05	57.8	.2040
355	8.22	47.2	.4340
356	9.32	17.0	----
357	2.47	----	----
358	4.39	85.0	.0442
359.	5.76	88.6	.0329
360	2.88	84.0	.0625

APPENDIX I

CALCULATION OF EXPLOSION PRESSURES

OF

HYDROGEN AND AIR MIXTURES

APPENDIX I

CALCULATIONS OF EXPLOSION PRESSURES OF HYDROGEN AND AIR

In the following discussion the theoretical explosion pressures developed by mixtures of hydrogen with various amounts of air will be calculated.

The equations and constants employed in the calculations are taken from a thesis by G. T. Felbeck, entitled, "A Mathematical Treatment to Determine the Temperature and Extent of Combustion in the Gas Engine." The writer is indebted to Mr. Felbeck for the material taken from his thesis.

In order to calculate the maximum pressure produced in the explosion of any inflammable gas mixture, it is necessary to take into account three factors:

1) The heat of combustion of the mixture.
2) The variation of the specific heat with temperature.
3) The dissociation of the products of the combustion into the initial constituents, thus rendering the reaction incomplete.

The mixture is assumed to be in a state of chemical equilibrium at the instant of attaining maximum pressure.

The following notation will be used in this Discussion:

T = temperature at equilibrium, deg. F. abs.

x = progress of the reaction.

P = maximum pressure (at equilibrium) lb. per sq. in. abs.

m = initial mixture, mols.

m' = mixture at equilibrium, mols.

γ_1 = mean molar specific heat of diatomic gases.

γ_5 = mean molar specific heat of hydrogen.

T_2 = initial temperature of mixture, deg. F. abs.

H_v = lower heating value of mixture at the temperature T, in Btu. per mol at constant pressure.

U_2 = initial energy of mixture.

U = energy of mixture at equilibrium (or maximum pressure)

K_p = equilibrium constant for the reaction.

n = number of mols of oxygen present.

The general method of procedure demands two equations involving the two unknown variables x and T.

By equating the energies of the mixture before explosion and at the time of equilibrium, we get

$$U_2 + xH_v = U$$

and

$$x = \frac{U - U_2}{H_v}$$

By inserting the usual expressions for specific heats and such constants as may be determined by the mixture, we get

$$x = \frac{(m-1)\gamma_1 T + \gamma_5 T - (m-1)\gamma_1 T_2 - \gamma_5 T_2}{H_v \text{ (at T deg.)}}$$

By substituting various values of T we may calculate corresponding values of x.

The equilibrium constant K_p is a function of the temperature and of x. It is defined in the hydrogen reaction as=

$$K_p = \frac{P_{H_2O}}{P_{H_2} \cdot \left[P_{O_2}\right]^{\frac{1}{2}}}$$

where n is the number of mols of oxygen present in the original mixture. K_p may be expressed in terms of x by setting up expressions for the partial pressures of the various gases and substituting them in the above equation. From the results of a number of experimenters' work, K_p is given as:

$$4.578 \log K_p = \frac{102100}{T} - 6.2631 \log T + 0.000236\, T$$
$$+ 0.0333 \cdot 10^{-6}\, T^2 + 1.1$$

Thus K_p may be calculated for any given temperature. After substituting the constants as determined by the mixture, and simplifying, we get

$$\log \frac{x}{1-x} \frac{1}{[n-\frac{x}{2}]} = \log K_p + \tfrac{1}{2}[\log \frac{P_2}{mT_2} + \log T] \qquad (2)$$

By substituting values of T we may calculate corresponding values of x. If Equations (1) and (2) are plotted, their point of intersection gives the values of x and T which will satisfy both equations.

The explosion pressure P may then be determined from T as follows:

$$P = \frac{m'T}{mT_2} P_2 \qquad (3)$$

The specific heat equations for the diatomic gases are as follows:

$$\gamma_1 = 4.51 + 0.2778\ T$$

$$\gamma_s = 4.51 + 0.25\ T$$

The lower heating value of hydrogen at constant volume is taken as 102930 Btu. per mol.

Case I. $H_2 + \frac{1}{2}O_2 + 1.9N_2$

Original mixture		Mixture at equilibrium	
H_2	1 mol	H_2O	x mols
O_2	0.5 "	H_2	1-x "
N_2	1.9 "	O_2	0.5x "
		N_2	1.9 "
m =	3.4 mols.	m' =	3.4 - 0.5x mols.

Energy equation=

$$x = \frac{2.4\gamma_1 T + \gamma_s T - 2.4\gamma_1 T_2 - \gamma_s T_2}{H_v}$$

Substituting values of T, we get

T	4000	4200	4400	4600	4800	5000
x	.675	.721	.772	.827	.884	.845

Equilibrium equation=

$$\log \frac{x}{1-x}\left[\frac{1}{0.5-0.5x}\right]^{0.5} = \log K_p + \frac{1}{2}\left[\log\frac{P_2}{3.4T_2} + \log T\right]$$

Substituting values of T, we get

T	4000	4400	4800	5000
x	.988	.975	.954	.939

Plotting these two sets of values (Fig. 54), the

values at the point of intersection are found to be

$$x = 0.940$$
$$T = 4983\ ^\circ F.\ abs.$$

From this value of T we calculate P as follows:

$$P = \frac{8.4 - 0.5 \cdot .940}{8.4} \times \frac{14.4 \cdot 4983}{535}$$

$$= 115.5 \text{ lb. per sq. in. abs.}$$

$$= 101.1 \text{ lb. per sq. in gage.}$$

Case II. $H_2 + O_2 + 3.8N_2$

From the energy and equilibrium equations we find

$$x = 1.000$$
$$T = 3667^\circ F.\ abs.$$
$$P = 90.0 \text{ lb. per sq. in. abs.}$$
$$= 75.6 \text{ lb. per sq. in. gage.}$$

Case III. $H_2 + 1.5O_2 + 5.7N_2$

From the energy and equilibrium equations we find

$$x = 1.000$$
$$T = 2842^\circ\ F.\ abs.$$
$$P = 69.8 \text{ lb. per sq. in abs.}$$
$$= 55.4 \text{ lb. per sq. in gage.}$$

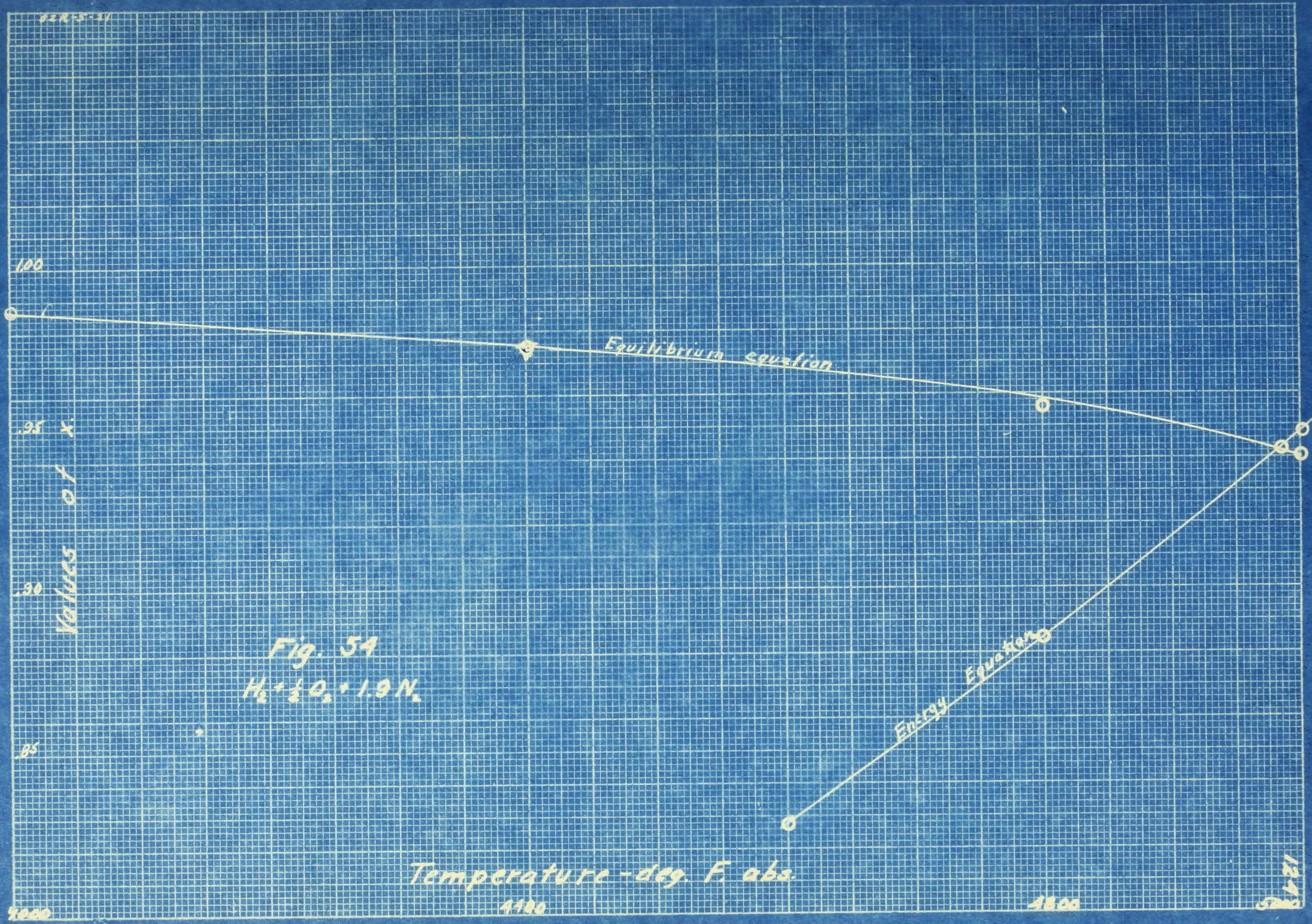


Fig. 54
$H_2 + \frac{1}{2}O_2 + 1.9N_2$